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Establishment of International Standards Organization (ISO) 5660 Acceptance Criteria for Fire Restricting Materials Used on High Speed Craft

FINAL REPORT
SEPTEMBER 1998

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Washington, DC 20593-0001

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16. Abstract (MAXIMUM 200 WORDS)

The U.S. Coast Guard is seeking to develop Cone calorimeter acceptance criteria to qualify linings, combustible components of furniture and other contents as fire restricting materials for high speed craft. In support, a research program was conducted at Southwest Research Institute between August 1997 and July 1998 to develop data for comparing the results of various fire tests. Eight composite materials and one textile wall covering were tested in the International Standards Organization (ISO) 9705 room. The same materials were also evaluated in small scale according to the test procedures of the Cone calorimeter, the International Maritime Organization (IMO) surface flammability test, and the IMO smoke and toxicity test. The ISO 9705 room tests and some of the Cone calorimeter experiments were supplemented with toxic gas analysis using Fourier Transform InfraRed (FTIR) spectroscopy. Some of the composite materials were used as framing materials for mock-up chairs and luggage racks for additional tests. This report covers the room tests, ISO 5660 Cone calorimeter tests, IMO surface flammability tests, and Lateral Ignition Flame Spread Test (LIFT) tests.

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METRIC CONVERSION FACTORS

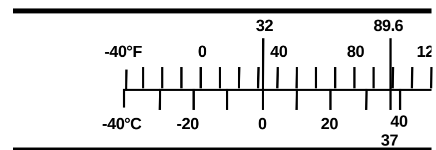
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	* 2.5	centimeters	cm
ft	feet	30.0	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

* 1 in = 2.54 (exactly).

Approximate Conversions

Symbol	When You Know	Multiply B
		LENGTH
mm	millimeters	0.04
cm	centimeters	0.4
m	meters	3.3
m	meters	1.1
km	kilometers	0.6
		AREA
cm^2	square centimeters	0.16
m^2	square meters	1.2
km^2	square kilometers	0.4
ha	hectares (10,000 m^2)	2.5
		MASS (WEIGHT)
g	grams	0.035
kg	kilograms	2.2
t	tonnes (1000 kg)	1.1
		VOLUME
ml	milliliters	0.03
l	liters	4.23
l	liters	2.1
l	liters	1.06
l	liters	0.26
m^3	cubic meters	35.32
m^3	cubic meters	1.3
		TEMPERATURE (EXA
°C	Celsius temperature	9/5 (then add 32)



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EXECUTIVE SUMMARY

On 1 January 1996, the High Speed Craft Code (HSC) entered into force as part of the Safety of Life at Sea (SOLAS) convention. This code deals with all aspects of the construction and operation of high-speed craft. The most common type of ships that are regulated by the code is passenger and vehicle ferries that operate within four hours from the shore. The code permits that a high-speed craft be constructed of combustible materials, provided certain fire performance criteria are met. Materials that meet these criteria are referred to as “fire restricting materials.” The determination of fire restricting materials is based primarily on one of two tests. Bulkhead linings and ceiling materials are tested using the International Standard Organization (ISO) 9705 room corner test. Acceptance criteria for ISO 9705 are published in resolution MSC.40(64) of the International Maritime Organization (IMO). Furniture components (other than fabrics, upholstery, or bedding) and other components are tested using the ISO 5660 Cone calorimeter. No acceptance criteria are published for ISO 5660.

The U.S. Coast Guard is seeking to develop Cone calorimeter acceptance criteria to qualify lining, furniture components, and other combustible components of contents as fire restricting materials for high-speed craft. In support, a research program was conducted at Southwest Research Institute between August 1997 and July 1998 to develop data for comparing the results of various fire tests. Eight glass fiber-reinforced composite materials and one textile wall covering were tested in full scale in the ISO 9705 room. The same materials were also evaluated in small scale according to the test procedures of the Cone calorimeter, the IMO surface flammability test (Part 5 of the IMO Fire Test Procedures or FTP Code), and the IMO smoke and toxicity test (Part 2 of the FTP Code). The ISO 9705 room tests and some of the Cone calorimeter experiments were supplemented with toxic gas analysis using Fourier Transform InfraRed (FTIR) spectroscopy. Some of the composite materials were used as framing materials for mock-up chairs and luggage racks. The upholstery of the chairs consisted of a foam/fabric combination that meets the requirements of IMO Resolution A.652(16), “Recommendation on Fire Test Procedures for Upholstered Furniture.” Room tests were conducted on these items. The primary objective of the additional full-scale tests was to determine whether the Cone calorimeter acceptance criteria for linings developed in this study, are suitable pass/fail limits for fire restricting materials used as components of contents. Additional ignition, flame spread, and release rate measurements were made to obtain material properties for modeling.

This report covers the room tests, ISO 5660 Cone calorimeter tests, IMO surface flammability tests, and Lateral Ignition Flame Spread Tests (LIFT).

The results of the ISO 9705 and IMO surface flammability tests are summarized in Table 1. Material Nos. 1 and 6 slightly exceeded the ISO 9705 smoke production limits for fire restricting materials. Material No. 6 is identical to Material No. 5, but painted with an intumescent coating. Material No. 7 did not exceed the ISO 9705 criteria for heat release and smoke production, but failed due to the fact that flaming debris fell to the floor during the test. However, flaming persisted for only a few seconds. Furthermore, this phenomenon occurred only once during the test.

Table 1. Summary of Room and Surface Flammability Test Data

Material	No.	ISO 9705	FTP Code Part 5
FR phenolic	1	Fail (no flashover)	Pass
Fire restricting material	2	Pass	Pass
FR polyester	3	Fail (flashover @ 6.2 min)	Fail
FR vinylester	4	Fail (flashover @ 5.3 min)	Fail
FR epoxy	5	Fail (flashover @ 16.5 min)	Pass
Coated FR epoxy	6	Fail (no flashover)	Pass
Textile wallcovering	7	Fail (no flashover)	Pass
Polyester	8	Fail (flashover @ 1.8 min)	Fail
FR modified acrylic	9	Fail (flashover @ 11.1 min)	Fail

The following set of ISO 5660 acceptance criteria for fire restricting materials is consistent with the results obtained in this study: 1) time to ignition (t_{ig}) greater than 20 seconds; 2) maximum 60-second sliding average heat release rate ($HRR_{60,max}$) less than 60 kW/m^2; 3) total heat release (THR) less than 12 MJ/m^2; 4) maximum 60-second smoke production rate ($SPR_{60,\ max}$) less than 0.01 m^2/second; and 5) average smoke production rate (SPR_{avg}) below

0.005 m^2/second. These values are averages from three tests conducted at a heat flux level of 50 kW/m^2 in the horizontal orientation using the retainer frame. These criteria are similar to those proposed to IMO by Finland in 1995, based on an analysis of data from the European Reaction to Fire Classification (EUREFIC) program.

The IMO surface flammability test criteria for finish materials appear to be correlative to the heat release rate criteria for fire restricting lining materials. Material No. 5 is the only material that met the IMO surface flammability criteria, but failed in the room/corner test due to excessive heat release. However, the time to flashover was the longest for this material, so there seems to be consistency between the two tests.

The room tests on contents confirmed that materials which meet the requirements for fire restricting linings could safely be used as framing materials and components of furniture and contents. The requirements could perhaps be relaxed, but a hazard or risk assessment is needed to develop revised acceptance criteria that do not compromise safety.

1.0 INTRODUCTION

On 1 January 1996, the High Speed Craft Code (HSC) entered into force as part of the Safety of Life at Sea (SOLAS) convention. This code deals with all aspects of the construction and operation of high-speed craft. The most common type of ships that are regulated by the code is passenger and vehicle ferries that operate within four hours from the shore. The code permits that a high-speed craft be constructed of combustible materials, provided certain fire performance criteria are met. Materials that meet these criteria are referred to as “fire restricting materials.” The determination of fire restricting materials is based primarily on one of two tests. Bulkhead linings and ceiling materials are tested using the International Standards Organization (ISO) 9705 room/corner test. Acceptance criteria for ISO 9705 are published in resolution MSC.40(64) of the International Maritime Organization (IMO). Furniture components (other than fabrics, upholstery, or bedding) and other combustible components of contents are tested using the ISO 5660 Cone calorimeter. No acceptance criteria are published for ISO 5660.

The U.S. Coast Guard is seeking to develop Cone calorimeter acceptance criteria to qualify linings, furniture components, and other combustible components of contents as fire restricting materials for high-speed craft. A research program was established to develop data for comparing the results of various fire tests. This program consisted of the following tasks:

- Select and procure eight composite materials with fire performance characteristics that span from excellent to poor. Add a thin finish material on a non-combustible substrate that meets the IMO surface flammability test criteria.

- Evaluate all materials in small scale according to the test procedures of ISO 9705 room test standard. Supplement room tests with toxic gas analysis.

- Evaluate all materials in small scale according to the test procedures of ISO 5660, the surface flammability test described in IMO Resolution A.653(16), and the Lateral Ignition and Flame Spread Test (LIFT). Supplement some ISO 5660 tests with toxic gas analysis. Evaluate all materials according to the smoke and toxicity test procedure described in Part 2 of the IMO Fire Test Procedures (FTP) Code.

- Attempt to determine appropriate ISO 5660 acceptance criteria for fire restricting materials using correlations and computer fire models to predict behavior in the ISO 9705 room tests on the basis of ISO 5660 data.

- Conduct full-scale tests on furniture and other contents of high speed craft compartments.

- Attempt to establish ISO 5660 acceptance criteria for the framing materials of furniture and contents on high-speed craft.

- Perform small-scale tests on the composite materials to determine whether the general IMO surface flammability requirements are consistent with and/or redundant to the acceptance criteria for fire restricting materials.

- Analyze the smoke and toxicity data to determine the necessity for smoke and toxicity testing, the appropriateness of the IMO smoke and toxicity test procedure, and the adequacy of the IMO smoke and toxicity acceptance criteria.

This report covers the room tests, ISO 5660 Cone calorimeter tests, IMO surface flammability tests, and LIFT tests. IMO smoke and toxicity tests and supplemental toxic gas analyses are covered in the report “Fire Smoke and Toxicity of Composites on High Speed Craft.”

2.0 SELECTION OF MATERIALS

2.1 Composite Materials

The first task of the original program was to develop a matrix of materials to be tested. The statement of work specified that materials shall be selected that, up to the maximum extent possible, are presently used, or are at least suitable for use, in the marine industry. The matrix had to cover a wide spectrum of fire performance, ranging from excellent to poor. In subsequent discussions with the U.S. Coast Guard, it was decided to include at least one material that is known to meet the criteria for fire restricting materials. A composite panel that performed successfully in the ISO 9705 room test at the Technical Research Center of Finland (VTT) was chosen for this purpose. This material consists of a phenolic-resin-impregnated glass fiber core, with melamine facings. It was also decided to include untreated marine grade polyester as the poorest fire performer.

Several prepreg manufacturers were contacted to obtain product information, and to find candidate suppliers for the remaining composites. The selection criteria were based on expected fire performance and cost. Table 2.1 provides peak heat release rate data at a heat flux level of 50 kW/m^2 for generic composites. The data in this table were obtained from the literature, and were used as guidance in the selection of materials.

Table 2.1 – Typical Peak Heat Release Rates for Composites

Material	Peak Heat Release Rate at 50 kW/m^2 (kW/m^2)
Epoxy	540
Vinylester	440
FR polyester	325
FR epoxy	250
FR vinylester	120
FR phenolic	75

Furthermore, it was also decided to evaluate one of the composites with and without an intumescent coating. Ideally, this composite should marginally fail to meet the requirements for fire restricting materials, so that the coating would improve performance of the material to pass the ISO 9705 room test criteria. Finland submitted a proposal to IMO for qualifying fire-restricting materials on the basis of Cone calorimeter data. The most recent version of the proposal indicates that a maximum 60-second sliding average heat release rate of 60 kW/m^2 or less in the Cone calorimeter at a heat flux of 50 kW/m^2 would be equivalent to meeting the ISO room test criteria for heat release rate. It was decided to obtain a double quantity of FR epoxy specimens, and to evaluate this composite material with and without a protective coating. Preliminary Cone calorimeter tests were conducted with different thicknesses of a water-based intumescent coating (0.5, 1, and 1.5 mm). Guided by the aforementioned proposal by Finland, the experimental data indicated that a coating thickness of 0.5 mm would probably be sufficient to obtain the desired room tests performance improvement.

The list of composite materials that were finally obtained for the experiments is given in Table 2.2. Some important characteristics are also provided in the table. All materials had a woven glass reinforcement, except Material No. 9, which was reinforced with chopped glass fibers. The glass content was obtained from the mass of a small specimen prior to and after heating overnight in an oven at 500°C. The materials are numbered in the order that they were received at SwRI.

Table 2.2 – Composite Materials Obtained for Testing

No.	Generic Name	Process	Thickness (mm)	Density (kg/m^3)	Glass Content (% by mass)
1	FR phenolic	Wet layup	3.8	1750	58
2	Fire restricting material	n/a	11.8	240	43
3	FR polyester	SCRIMP*	5.2	1650	55
4	FR vinylester	SCRIMP*	4.8	1630	58
5	FR epoxy	Wet layup	3.9	1910	71
6	Coated FR epoxy	Wet layup**	3.9**	1910**	71**
8	Polyester	Wet layup	4.1	1390	34
9	FR modified acrylic	SCRIMP	5.2	1880	66

* Uneven resin flow in fabrication resulted in poor quality panels and might have affected fire test performance.
** Characteristics for composite without coating (identical to Material No. 5).

2.2 Wall Covering Material

The modification to the original program specified that a thin finish material on a noncombustible substrate had to be added to the list of linings. The objective was to determine how a material that meets the IMO surface flammability requirements would behave in the ISO 9705 room/corner test. This information is useful in comparing general IMO surface flammability requirements to the criteria for fire restricting materials. A list of materials that received type approval by the U.S. Coast Guard for IMO surface flammability testing was reviewed, but most of these materials are thin plastic veneers that were not found to be suitable. Finally, a paperbacked textile wall covering was selected that does not appear on the U.S. Coast Guard list of type approvals. According to information received from the manufacturer, this material meets the IMO surface flammability requirements based on test results obtained by VTT in Finland. The wall covering was adhered to an inorganic reinforced cement board with a thickness of 6.4 mm and a nominal density of 1760 kg/m^3. The wall covering is identified as Material No. 7.

2.3 Furniture Upholstery

Two types of flexible foams, two types of fabrics, and an interliner were obtained to make cushions for chair mock-up tests. Various combinations of foams and fabrics, with and without interliner, were evaluated in the Cone calorimeter. Based on the Cone calorimeter data, a foam that meets California Technical Bulletin 117 (CAL TB 117), and a FR-treated wool fabric were selected. Tests were conducted according to the procedure described in IMO Resolution A.652(16), “Recommendation on Fire Test Procedures for Upholstered Furniture.” The results from these tests confirmed that the foam/fabric combination would be acceptable for use as furniture upholstery on high speed craft, and the combination was therefore selected for the chair mock-up tests described in Section 4.

3.0 ROOM/CORNER TESTS ON LININGS

3.1 Introduction

Nine materials were tested in accordance with the procedures outlined in ISO 9705, " Fire tests – Full-Scale Room Test for Surface Products." This test protocol is used to evaluate the contribution to fire growth (specifically, heat release rate, flame spread, and smoke production) provided by a surface or wall covering product using a specified ignition source. The test results can be used to classify a material as either fire resistant or non-fire resistant, as well as an aid in determining its appropriateness for use in a particular application.

3.2 Room/Corner Test

3.2.1 Test Setup

Apparatus – The apparatus (also described in ISO 9705) consisted of a room measuring 3.6 m deep by 2.4 m wide by 2.4 m high, with a single ventilation opening (doorway) measuring 0.8 m wide by 2 m high in the front wall. The walls were constructed of noncombustible calcium silicate boards with a nominal density of approximately 750 kg/m^3 and a thickness of 20 mm. During testing, the interior surfaces of all walls (except the front wall) and the ceiling were covered with a combustible lining material that was exposed to a propane burner ignition source. The burner was located on the floor in the back right corner of the room opposite the doorway (right when looking through the doorway into the room). Heat release rate was measured on the basis of oxygen consumption. Instrumentation for measuring rate of heat release and smoke production were installed in the exhaust duct of a fume collection hood located outside the room immediately adjacent to the doorway. The duct instrumentation consisted of thermocouples for measuring exhaust gas temperature, a bi-directional probe for measuring exhaust gas velocity, a collimated light system for measuring smoke obscuration, and probes for sampling oxygen and carbon dioxide concentration. The room also contained a single heat flux gauge located in the center of the floor and seven thermocouples. A thermocouple was located in each of four ceiling quadrants, the center of the ceiling, immediately above the burner, and along the top edge of the doorway. Each thermocouple was located either 10.16 centimeter (cm) (4 inches) below the ceiling, or 10.16 cm below the top of the doorway.

Specimen – Each material was obtained from the supplier in the form of panels measuring approximately 1.22 x 2.44 m (4 x 8 ft) and of the appropriate thickness. To completely line the room, 11 panels were required; three on each side wall, two on the back wall, and three on the ceiling. The panels were secured to the room walls and ceiling with wood screws. The screw heads were recessed and then covered with an intumescent coating to prevent excessive heat transfer to the panels and room structure.

Ignition Source – The burner consisted of a thin gauge steel box measuring approximately 0.17 x 0.17 x 0.152 m deep filled with pea gravel. Propane of at least 98% purity is metered into the burner from a pipe which extends through one side and into the bottom of the box. The pea gravel aids in dispersing the propane vapors to achieve a uniform flame over the top surface of the box. During the test, the burner was located on the floor in the back right corner of the room. The test procedure dictates that the propane flow rate be set such that a heat release rate of 100 kW is achieved at the burner for the first ten minutes of the test, followed by 300 kW for the remaining ten minutes. Propane mass flow rate is measured utilizing a series of calibrated mass flow meters.

3.2.2 Calibration Procedure

As described in ISO 9705, calibration of the propane burner and exhaust duct heat release rate measuring instrumentation is conducted with the burner positioned one meter below and in the center of the exhaust hood. To be a valid calibration, calculations of the steady-state heat release rate, as determined from exhaust duct measurements, must be within 5% of the calculated steady-state burner heat release rate, as determined from the propane mass flow measurements. The calibration is performed utilizing the burner heat release rate schedule shown in Table 3.1. Measurements are taken every six seconds starting two minutes prior to ignition of the propane burner.

Table 3.1 – Calibration Schedule

Time Span (minutes)	Burner Heat Release Rate (kW)
0 – 2	0
2 – 7	100
7 – 12	300
12 – 17	100
17 – 19	0

3.2.3 Test Procedure

To begin the test, the specimen was installed in the room, followed by installation and checkout of all instrumentation and data recording devices. Data recording was started at least two minutes prior to ignition of the propane burner. Thirty seconds prior to burner ignition, video recording commenced. After ignition, the propane flow rate was adjusted to achieve a burner heat release rate of 100 kW and maintained at this level for the first ten minutes of the test. The hood exhaust capacity was initially established at approximately one m^3/second, but was slowly increased as needed to ensure capture of all combustion products (i.e., smoke). Ten minutes after ignition of the burner, the burner heat release rate was increased to 300 kW and maintained at this level for an additional ten minutes.   Testing was terminated after 20 minutes or at the instant of flashover, whichever occurred first.

3.2.4 Results

The test results are used to classify a material as either fire restricting or non-fire restricting. To qualify a material as fire restricting, the following requirements listed in IMO Resolution MSC.40(64) must be met: 1) test average heat release rate over the entire test time shall not exceed 100 kW; 2) maximum 30-second average heat release rate shall not exceed 500 kW; 3) test average smoke production rate shall not exceed 1.4 m^2/second; 4) maximum 60-second average smoke production rate shall not exceed 8.3 m^2/second; 5) no flame spread to area below

0.5 m from the floor at distance greater than 1.2 meters (m) from corner; and 6) no flaming droplets or debris may reach the floor, except in an area within 1.2 m from the corner.

3.3 Calibration Data

Prior to beginning the Room/Corner test series, a calibration of the propane burner and exhaust hood heat release rate instrumentation was conducted. The results are shown in Figure 3-1. The burner heat release rate value was calculated from measurements of the propane mass flow rate. Exhaust hood heat release rate was calculated from measurements of duct temperature, velocity, and O_2/CO_2 concentration.

Figure 3.1 – Comparison of Heat Release Rate for Burner and Exhaust Hood Calculated from Calibration Data

3.4 Test Data

A summary of the test results relevant to the fire-restricting criteria outlined in Section 3.2.4 are provided in Table 3.2. For those materials in which flashover was observed, the flashover time (after burner ignition) is presented in Table 3.3. Note that flame spread data is not presented. For those materials in which flashover was not observed, flames did not spread to within 0.5 m of the floor. Where flashover was observed, the test was terminated before flames reached the 0.5-m position. Photographs at various times during the room corner tests can be found in Appendix A1, and plots of heat release rate, smoke production, floor heat flux, and room temperatures are provided for each material in Appendix A2.

Table 3.2 – Summary of Test Results – Heat Release Rate and Smoke Production

Material	Heat Release Rate (kW)			Smoke Production (m^2/s)			Pass
	30s Avg.	Net Avg.	Pass	60s Avg.	Net Avg.	Pass	
1	197.7	47.7	Y	9.4	2.2	N	N
2	143.9	25.7	Y	0.8	0.2	Y	Y
3	1515.8	138.8	N	49.4	10.3	N	N
4	1435.8	196.8	N	54.7	14.8	N	N
5	686.3	113.6	N	42.9	10.2	N	N
6	166.1	28.6	Y	5.8	2.1	N	N
7	140.8	20.7	Y	0.3	0.2	Y	Y
8	1734.6	273.9	N	22.3	4.9	N	N
9	963.1	131.7	N	8.7	1.1	N	N
Criteria	≤ 500kW	≤ 100kW		≤ 8.3	≤ 1.4		

Table 3.3 – Time to Flashover

Material	Time to Flashover
3	6.2 minutes
4	5.3 minutes
5	16.5 minutes
8	1.8 minutes
9	11.1 minutes

Only Material No. 2 met all the criteria, and can be classified as a fire restricting material. Material No. 7 met the heat release rate and smoke production criteria. This material consisted of a thin wall covering adhered to a non-combustible substrate (glass fiber reinforced cement board). The wall covering tended to separate from the substrate during the room test. As a result, pieces of the burning wallpaper dropped onto the floor and self extinguished. Although this behavior is not allowed by the test standards, the authors did not view it as a problem. Therefore, for the purposes of this study, this behavior is ignored and the data are used as if the material would pass.

3.5 Conclusions

Application of the test procedures and pass/fail criteria outlined in ISO 9705 to this program revealed a few shortcomings with the standard. First, no exhaust duct volumetric flow rate or range of flow rates are specified in the test procedure. The calibration procedure does provide for an examination of the effect of duct flow rate, but only at the 300 kW level. However, our experience has shown that the exhaust volumetric flow does affect the heat release rate measurements and the effect is usually greater at the lower flow rates and heat release values. More importantly, the heat release rate tends to show unreal spikes when the duct volumetric flow rate is suddenly increased. Rapid increases in duct flow rate may occasionally be necessary when a sudden increase in smoke production is experienced. This phenomenon needs to be investigated more fully and then addressed in the appropriate test standards.

In this program, the flame spread failure criteria (to within 0.5 m of the floor) was not an issue for any of the materials tested. For those materials which burned for the required 20 minutes without flashover, flames were confined to the wall and ceiling area in the immediate vicinity of the burner flame. Where flashover occurred, smoke and heat release rate upper limits were exceeded before flames spread to the 0.5-m level. Since we feel that a representative range of fire restricting and non-fire-restricting materials were tested in this program, it is likely that this effect is also representative. Thin wallpaper type coverings may be a possible exception. Due to the small amount of material involved, it may be possible for these materials to experience significant flame spread without exceeding the heat release rate or smoke production limits. However, in light of our recent experience, flashover may still occur before flames reach the 0.5-m level. Thus, a reexamination of this failure criterion is perhaps in order.

Although it may not be representative, the wallpaper tested here (Material No. 7) tended to separate from its substrate and fall to the floor. Even though this behavior is not allowed for fire restricting materials, we did not view it as a problem in this application. Since the quantity of falling debris was very small and flaming ceased in a few seconds, the data are used in this report as if the material would pass.

Lastly, ISO 9705 specifies that the entire room be lined with the material to be tested (except the front wall). Observations from this test series revealed that this requirement might not be necessary. In most cases, only the panel sections adjacent to the burner, those at the top of the side walls, and those on the ceiling burned during the test. Generally, the remainder of the test specimen panels did not contribute significantly to the fire. Thus, we conclude that a partially lined room may be adequate to assess the fire-restrictive nature of a wall covering material. For future testing, this requirement should be assessed in light of the cost of the additional material required to fully line the room.

4.0 ROOM TESTS ON CONTENTS

4.1 Introduction

Two different types of test series were conducted to assess the fire-resistive behavior of materials when used as room contents. In the first test series, the materials were tested in the form of either single or double chairs located inside the ISO 9705 room described in Section 3.0. The test protocol followed the procedures outlined in ASTM E 1537, “Standard Test Method for Fire Testing of Upholstered Furniture Items,” and California Technical Bulletin 133, “Flammability Test Procedure for Seating Furniture for Use in Public Occupancies.” These test standards measure the fire performance characteristics of representative full-scale upholstered furniture, and provide an aid in determining their suitability for use in public occupancies.

The second test series was of SwRI design and measured the fire performance characteristics of the same materials when configured as overhead luggage racks or compartments representative of those found on passenger aircraft, trains, busses and water craft. Again, the ISO 9705 room was used as the test apparatus with the luggage rack positioned across the back wall above the propane burner. Use of the ISO 9705 room and associated instrumentation allowed for comparisons of heat release rate, smoke production, and room temperatures to those observed when the same materials were tested as room lining materials. Although the same failure criteria specified in ISO 9705 could not be strictly applied (due to the more limited quantities of material and different configuration), the data is useful as a guide in determining the suitability of such materials for use in luggage racks.

4.2 Furniture Tests

4.2.1 Test Setup

Apparatus **–** The test setup consisted of placing ether a single upholstered chair or two identically upholstered chairs on a load cell located inside the previously described ISO 9705 room (see Section 3.2.1). A portable square propane burner was used to ignite the upholstery.

Instrumentation for measuring rate of heat release and smoke production was installed in the exhaust duct of a fume collection hood located outside the room immediately adjacent to the doorway. The duct instrumentation consisted of thermocouples for measuring exhaust gas temperature, a bi-directional probe for measuring exhaust gas velocity, a collimated light system for measuring smoke obscuration, and probes for sampling oxygen and carbon dioxide concentrations. Note that smoke obscuration was measured in the exhaust duct instead of inside the room as described in TB 133 and ASTM E 1537. Experience gained from the previous room lining tests indicated that most of the smoke gathered near the ceiling before exiting the room and being captured by the exhaust hood system. ASTM E 1537 dictated placement of the smoke measurement system at room mid height. Measurement at this location would have resulted in a lower than actual smoke number. Thus, it was felt that a more representative smoke number could be obtained by measurement in the exhaust duct. Heat release rate was measured on the basis of oxygen consumption, as before.

The room also contained two thermocouples and a load cell. One thermocouple was located over the geometric center of the square propane burner, 25-mm (1 inch) below the ceiling. The other thermocouple was located at a distance of 0.91 m (3 feet) in front of the burner and 1.22 m (4 feet) below the ceiling. A load cell was used to measure the mass loss of the chairs as they burned. It was located on the floor along the back wall, opposite the doorway. A sheet of gypsum board placed between the top surface of the load cell and the chairs was used to protect it from the heat of the fire. Lastly, calibrated mass flow meters were used to measure propane mass flow.

Specimen – Each chair consisted of a steel frame into which was placed upholstered seat and back cushions, as well as non-upholstered side panels. The frame was constructed of welded 1 x 1 x 1/8 steel angles. The seat and back cushions were constructed from flat panels of the test material with a 2-inch thick section of polyurethane foam covered with a wool fabric to simulate typical commercial furniture upholstery. Each seat cushion measured approximately 45 x 45 cm whereas the back cushion measured approximately 45 x 33 cm. Two side pieces were formed from bare flat pieces of the test material measuring approximately 41 x 66 cm. The side pieces extended on each side of the chair from under the steel frame arm rests to the extreme bottom of the chair. The cushions and side panels were attached to the metal frame with sheet metal screws. When two chairs were tested, they were placed side by side, equally spaced over the load cell, and separated from each other by approximately 10.2 cm (4 inch).

Ignition Source – The propane burner was a 250 x 250-mm (10 x 10-inch) square burner constructed of ½-inch outside diameter (OD) x .035 inch wall stainless steel tubing. On the forward side of the burner (toward the chair back) were placed two series of 1-mm diameter holes. One series consisted of 14 holes oriented horizontally outward with spacing between holes of 13 millimeters (mm). The other series consisted of nine holes orientated downwards, also with a 13-mm spacing. Along the right and left sides of the burner were placed 6 holes pointing horizontally outward and four holes pointing downward at a 45 degree angle. These holes were also 1 mm in diameter with spacing between holes of 13 mm. Propane of at least 98% purity was supplied to the square burner through a similar section of tubing which was welded to the rear of the front side and extended rearward and upward at a 30 degree angle (see ASTM E 1537 for a detailed description).

4.2.2 Calibration Procedure

Calibration of the square burner was conducted with the burner placed one meter (m) below and in the geometric center of the exhaust hood. Calculations of the steady-state heat release rate, as determined from exhaust duct measurements, were then compared to the calculated steady-state burner heat release rate as determined from measurements of propane mass flow. The propane flow rate was established at 13 liters (l)/minute, (approximately 19.3 kW) as specified in ASTM E 1537. The propane flow rate was maintained for approximately seven minutes. Measurements were taken every six seconds, starting two minutes prior to ignition of the propane burner.

4.2.3 Test Procedure

To begin the test, the chair(s) are placed inside the room, along the back wall, and on top of the load cell. All instrumentation is installed and verified prior to beginning the test. The burner is placed 2.54 centimeters (cm) (1 inch) above the seat cushion with the front side of the burner positioned 5 cm (2 inches) forward of the back cushion. When two chairs are tested, the burner is placed over the left chair (when looking through the room doorway). Data and video recording devices are then started. At the two-minute mark, the propane flow (previously established at 13 liters/minute) is started and the burner ignited. The chair is exposed to the burner for 80 seconds, and then the burner is removed. The chair is observed to determine if the flames are extinguished, or if they spread to other parts of the chair or to the adjacent chair when present. Heat release rate, smoke production, room temperature (from the two thermocouples), and chair mass loss are determined as functions of time. The test is terminated when all signs of burning (flames, smoke, smoldering, etc.) have ceased.

4.2.4 Results

The test results are used to determine the suitability of a particular furniture item for use in a public or commercial occupancy. Although ASTM E 1537 contains no pass/fail criteria, California Technical Bulletin 133 considers seating furniture unsuitable if the calculated net heat release rate exceeds 80 kW.

4.2.5 Calibration Data

Prior to beginning the Room/Corner test series, a calibration of the propane burner and exhaust hood heat release rate instrumentation was conducted. The results are shown in Figure 4.1. The burner heat release rate value was calculated from measurements of the propane mass flow rate. Exhaust hood heat release rate was calculated from measurements of duct temperature, velocity, and O_2/CO_2 concentration.

Figure 4.1 – Comparison of Heat Release Rate for Burner and Exhaust Hood Calculated from Calibration Data Obtained Prior to Furniture Test Series

4.2.6 Test Data

A summary of the peak net heat release rate and smoke production data is presented in Table 4.1. For a single chair configuration, all materials passed the TB 133 criteria. However, when two chairs were tested in a side by side arrangement, only the steel baseline and Material No. 5 passed. Missing data in the table indicates that this configuration was not tested. Plots of heat release rate, smoke production, mass loss, and room temperatures are provided for each material and configuration tested in Appendix B2.

Table 4.1- Furniture Test Results – Heat Release Rate and Smoke Production

Material	Peak Net Heat Release Rate		Peak Smoke Production Rate		TB 133 Pass	
	Single Chair	Double Chair	Single Chair	Double Chair	Single Chair	Double Chair
Steel	32 kW	41 kW	0.5 m^2/s	0.5 m^2/s	Y	Y
1	46 kW	125 kW	1.5 m^2/s	2.7 m^2/s	Y	N
4	46 kW		1.2 m^2/s		Y	
5	34 kW	38 kW	0.8 m^2/s	0.5 m^2/s	Y	Y
8		320 kW		19.5 m^2/s		N

4.3 Luggage Rack Tests

4.3.1 Test Setup

Apparatus – The apparatus (also described in ISO 9705) was described in Section 3.2.1 except for the placement of the test sample. During testing, the luggage rack was mounted just below the ceiling and extended across the entire back wall of the room (wall opposite the doorway). The burner was located on the floor in the back right corner of the room opposite the doorway (right when looking through the doorway into the room). Instrumentation for measuring rate of heat release and smoke production was installed in the exhaust duct of a fume collection hood located outside the room immediately adjacent to the doorway. The duct instrumentation consisted of thermocouples for measuring exhaust gas temperature, a bi-directional probe for measuring exhaust gas velocity, a collimated light system for measuring smoke obscuration, and probes for sampling oxygen and carbon dioxide concentration. Heat release rate was measured on the basis of oxygen consumption. The room also contained a single heat flux gage located in the center of the floor and seven thermocouples. A thermocouple was located in each of four ceiling quadrants, the center of the ceiling, inside the luggage rack immediately above the burner, and along the top edge of the doorway. Each thermocouple was located either 10.16 cm (4 inches) below the ceiling or 10.16 cm (4 inches) below the top of the doorway.

Specimen – Each material was obtained from the supplier in the form of panels measuring approximately 1.22 x 2.44 m (4 x 8 feet) and of the appropriate thickness. To form the luggage rack, the vendor-supplied panels were cut and installed into a steel frame. The frame consisted of welded 1 x 1 x 1/8 angles which formed an open elongated box measuring approximately 2.44 m (96 inches) long, 0.53 m (21 inches) high and 0.3 m (12 inches) deep. It was mounted along the back wall of the test room, approximately 1.27 cm (0.5 inch) below the ceiling, and oriented such that the elongated side (2.44 m dimension) extended across the entire width of the room, with its height (0.53 m dimension) extending down from the ceiling. The front face of the luggage frame was additionally divided by three equally spaced angles. Thus, six flat panels of the test material were installed into the steel frame. Four panels, each measuring 0.61 x 0.5 m (24 x 21 inches), were installed across the front face (between the equally spaced angles), and two panels, each measuring 0.3 x 1.22 m (12 x 96 inches), formed the bottom of the luggage rack. All panels were attached to the steel frame with machine screws. Lastly, seven standard reams of paper (500 sheets each of paper weighing 75 g/m^2 were placed inside the luggage rack and evenly distributed in seven stacks along the bottom. The walls of the room were not lined, and the luggage rack constituted the only combustible item in the room.

Ignition Source – The ignition source for the luggage rack tests was the same as for the ISO 9705 room tests on linings, and was described in Section 3.2.1.

4.3.2 Calibration Procedure

The calibration was as per ISO 9705, as described in Section 3.2.2.

4.3.3 Test Procedure

To begin the test, the specimen was installed in the room, followed by installation and checkout of all instrumentation and data recording devices. Data recording was started at least two minutes prior to ignition of the propane burner. Thirty seconds prior to burner ignition, video recording commenced. After ignition, the propane flow rate was adjusted to achieve a burner heat release rate of 100 kW and was maintained at this level for the first ten minutes of the test. The hood exhaust capacity was initially established at approximately 1 m^3/s, but was slowly increased as needed to ensure capture of all combustion products (i.e., smoke). Ten minutes after ignition of the burner, the burner heat release rate was increased to 300 kW and maintained at this level for an additional ten minutes. Testing was terminated after 20 minutes or at flashover, whichever occurred first. During the test, heat release rate, floor heat flux, room temperatures, and smoke obscuration were recorded as functions of time.

4.3.4 Results

Since the Luggage Rack Test was of SwRI design, no regulatory pass/fail criteria can be quoted. However, the results, when used in combination with the furniture and room linings test results, should be useful as a guide in determining the suitability of each material for application to luggage racks and similar categories of room furnishings.

4.3.5 Calibration Data

Since the same burner was used for both the Room Linings and Luggage Rack Tests, only one calibration sequence was conducted. Thus, the reader is referred to Section 3.3 for a discussion of the calibration results.

4.3.6 Test Data

Table 4.2 summarizes the peak net heat release rate and smoke production data obtained during the Luggage Rack Tests. Plots of heat release rate, smoke production, floor heat flux, and room temperatures for each material tested are provided in Appendix B2.

Table 4.2 – Luggage Rack Test Results – Heat Release Rate and Smoke Production

Material	Peak Net Heat Release Rate (kW)	Peak Smoke Production Rate (m^2/s)
Steel	0	0.3
1	30[1]	0.4[1]
4	110	10.3
5	40	2.5
8	325	7.5

Note 1: Equipment malfunction, test terminated before completion.

4.4 Conclusions

The test results clearly demonstrate that the results obtained from standard furniture flammability tests should be used with judgement and caution. When testing a single chair, all the materials easily passed the TB 133 criteria, and thus, would have been found acceptable for use in public occupancies where TB 133 compliance is required. However, when a second chair was added to the scenario, only one material passed (in addition to the steel baseline). Our results demonstrate that the total quantity of material present must be considered when assessing the suitability of furniture and other room furnishings. A more appropriate use of standard furniture flammability test results would be as inputs to a more detailed hazard assessment, where total quantity of flammable material present, their specific locations, and intended use can be taken into account and the effect of active fire protection measures can be considered.

5.0 CONE CALORIMETER TESTS

5.1 Introduction

All lining materials were tested in accordance with ISO 5660 “Fire Tests – Reaction to Fire – Heat Release Rate of Building Products.” This standard was published in 1993, and does not include dynamic smoke measurements. A new version of the ISO 5660 standard is currently (summer 1998) being balloted in several parts by ISO/TC92/SC1. Part 1 of the new version covers the same subjects as the 1993 standard, i.e., a description of the Cone calorimeter test apparatus and instrumentation; calibration procedures; and methods for measuring heat release rate, mass loss rate, and time to ignition. Dynamic smoke obscuration measurements based on a laser photometer form the subject of Part 2. Part 3 describes a stripped-down version of the Cone calorimeter suitable for quality control based on mass loss measurements. Part 4 is a general guidance document for Cone calorimeter operators and users of Cone calorimeter data. The new version of ISO 5660 is much more detailed and complete (it includes dynamic smoke obscuration measurements) than the present standard. It is expected that the current ballot will be successful, and that the new edition of ISO 5600 will be published soon. Therefore, it was decided to obtain and review the latest drafts of Parts 1 and 2 of ISO 5660. The Cone calorimeter tests in this program were generally conducted according to the provisions in these draft standard documents. ASTM Standard E 1354, “Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter” is very similar to the new ISO 5660 standard, and was also consulted for guidance during this program.

The Cone calorimeter was developed primarily to measure the heat release rate from solid materials over a wide range of thermal exposure conditions. The apparatus is also used to evaluate the ignition propensity of materials, to determine the mass loss rate, and to measure the generation rate of smoke and other products of combustion. The Cone calorimeter is used primarily for research and development purposes, and is suitable for obtaining fundamental material properties that can be used in conjunction with mathematical models to predict the performance of materials and systems in real fires.

IMO Resolution MSC.40(64) specifies that furniture components (other than fabrics, upholstery, or bedding) and other combustible components of contents be tested according to the ISO 5660 Cone calorimeter standard, to demonstrate that they qualify as fire restricting materials. However, neither test conditions nor acceptance criteria are specified in the IMO Resolution. In

April 1995, Finland submitted a proposal for ISO 5660 acceptance criteria to the Subcommittee on Fire Protection of IMO. It was suggested that surface linings qualify as fire restricting materials if the following criteria are fulfilled for the average results from three tests conducted according to ISO 5660-1 (time to ignition and heat release rate) and ISO 5660-2/ASTM E 1354 (smoke production). The tests shall be conducted for 20 minutes at a heat flux level of 50 kW/m^2, in the horizontal orientation, with the ignition spark and retainer frame.

- Time to ignition (t_{ig}) greater than 30 seconds.
- Maximum 60-second sliding average heat release rate ($HRR_{60,max}$) less than 50 kW/m^2.
- Total heat release (THR) less than 12 MJ/m^2.
- Maximum 60-second sliding average smoke production rate ($SPR_{60, max}$) less than 0.02 m^2/s.
- Average smoke production rate (SPR_{avg}) below 0.003 m^2/s.

A month later, Finland proposed to drop the requirements for $SPR_{60, max}$, to increase the limit for SPR_{avg} to 0.004 or 0.005 m^2/s, to increase the limit for $HRR_{60, max}$ from 50 kW/m^2 to 60 kW/m^2. The proposals were based on an analysis of data from the EUREFIC program (a research program that was conducted in the Nordic countries between 1989 and 1991 with the objective to develop a reaction-to-fire classification system for linings in buildings based on performance in the ISO 9705 room/corner test and the ISO 5660 Cone calorimeter). Although the proposals were not accepted, the limits suggested by Finland provide a very useful starting point toward reaching the main objective of this program.

5.2 Cone Calorimeter

5.2.1 Apparatus and Test Procedure

In 1917, Thornton (*Philosophical Magazine and Journal of Science*, Vol. 33) showed that for a large number of organic liquids and gases, a nearly constant net amount of heat is released per unit mass of oxygen consumed for complete combustion. Sixty years later, researchers at National Bureau of Standards (NBS) found this to also be true for organic solids and obtained an average value for this constant of 13.1 MJ/kg of O_2. This value may be used for practical applications and is accurate with very few exceptions to within ± 5%. Thornton's rule implies that it is sufficient to measure the oxygen consumed in a combustion system in order to determine the net heat released. This technique, generally referred to as the "oxygen consumption technique," is now the most widely used and accurate method for measuring heat release rate in experimental fires. The Cone calorimeter is a small-scale instrument to measure rate of heat release of solid materials under a wide range of conditions, using the oxygen consumption technique. A schematic of the instrument is shown in Figure 5.1.

Figure 5.1 — Schematic of the ISO 5660 Cone Calorimeter

In the Cone calorimeter, a square sample of 100 x 100 mm is exposed to the radiant flux of an electric heater. The heater has the shape of a truncated cone (hence the name of the instrument) and is capable of providing heat fluxes to the specimen in the range of 10-110 kW/m^2. An electric spark plug is used for piloted ignition. Heater temperature is measured as an average of the readings of three thermocouples in contact with the coil. It is set and maintained at a certain level by a three-term controller. Calibration of heat flux as a function of heater temperature is performed with a total heat flux meter of the Schmidt-Boelter type.

Prior to testing, the heater temperature is set at the appropriate value resulting in the desired irradiance. At the start of a test, the specimen in the appropriate holder is placed on the load cell, which is located below the heater. The load cell has a tare adjustment. This allows for a mechanical shift of the zero so that high accuracy mass loss measurements can be made, even if the mass of the holder and a possible substrate are much higher than that of the specimen. As soon as the pyrolysis products released by the specimen ignite, the electric spark plug is removed. All combustion products and entrained air are collected in the hood. An orifice plate at the entrance of the exhaust duct results in an almost uniform gas mixture. At a sufficient distance downstream from the mixing orifice, a gas sample is taken and analyzed for O_2. A laser photometer is located close to the gas sampling point to measure light extinction by the smoke.

The exhaust gases are removed by a cast iron high-temperature fan. The blower is driven by a DC motor with thyristor speed control. The flow rate can be adjusted between 0 and 50 liters per second. For standard testing, the Cone Calorimeter is used in constant volume mode and the fan speed is set at 24 liters per second. Downstream of the fan is a second orifice plate. Measurements of the differential pressure across and gas temperature at the orifice plate are used for calculating the mass flow rate of the exhaust gases.

5.2.2 Calibration Procedure

The present ISO 5660 standard is rather prescriptive, as it is based on the original apparatus designed by Dr. Vytenis Babrauskas in the early 1980s. One of the major differences in the new draft is that there is a lot more flexibility in the selection of major components and instrumentation. Instead of prescribing exactly which components have to be used, a set of performance criteria are provided for each of the major components. Detailed calibration procedures are included to verify whether the components and instruments meet the criteria.

5.2.3 Test Procedure

Standard specimens measure 100 x 100 mm, and can be up to 50 mm thick. Specimens are wrapped in thick aluminum foil, and are placed in the specimen holder on low-density ceramic fiber blanket. Most materials are tested with a stainless steel retainer frame, which protects the edges from direct thermal exposure and provides some restraint for materials that warp or intumesce when heated. At the start of the day before the heater is turned on, the distance between the heater base plate and the specimen surface is measured and adjusted to 25 mm, if needed. Then, power to the heater is turned on, and the heater temperature controller is set to a level that approximately corresponds to the desired heat flux level. The heat flux is verified with a heat flux meter of the Schmidt-Boelter type, and is adjusted to the desired level, if necessary. At the start of a test, a steel plate is inserted below the heater, the holder with specimen is placed on the load cell, the plate is removed and the spark plug is energized and swung into place. The test is aborted if ignition does not occur within ten minutes (this was increased to 20 minutes for this program). Tests are terminated two minutes after all flaming has ceased, or after 62 minutes (reduced to 22 minutes for this program), whichever occurs first. The data acquisition system starts collecting baseline data one minute prior to a test. The signals from the various instruments (thermocouples, load cell, oxygen analyzer, pressure transducer, etc.) are recorded at a user-specified interval ranging from two (for materials that burn for a very short time) to five (standard sampling interval) seconds.

5.2.4 Results

One is easily overwhelmed with the massive amounts of data that the Cone calorimeter provides. The data sheets in Appendix C2 provide all the results and information that is required to be reported by the ISO and ASTM standards.

5.3 Calibration Data

The performance characteristics (noise and drift, response, linearity, etc.) of the main components and instruments (load cell, heater control system, oxygen analyzer, flow measuring system, and laser photometer) were checked at the start of the program, and were found to be in compliance with the requirements in the ISO 5660 drafts. At the start of each day, the oxygen analyzer was calibrated with zero and span gas,[1] and a 5-kW methane gas burner calibration was performed to check the orifice coefficient. A coefficient that is significantly different (discrepancies of 10% or greater) from the theoretical value indicates that there is a problem that needs to be addressed. The overall linearity of the heat release rate measurements was verified with gas burner calibrations at 1, 3, and 5 kW, and was found to be within 1%.

5.4 Test Results

Specimens of the eight composite materials and the thin finish material were tested in duplicate at 25, 50, and 75 kW/m^2. Only Material No. 9 was tested in triplicate at each level. Additional tests were conducted at 100 kW/m^2 on materials that did not ignite at 25 kW/m^2. Thus, complete Cone calorimeter data were obtained at three heat flux levels for all materials, except No. 2, which did not ignite at 50 kW/m^2.

For materials that are less than 6 mm in thickness, ISO 5660 recommends that the specimens be tested in combination with the same substrate as used in practice. Since the thickness of most materials was less than 6 mm, specimens were backed by a calcium silicate board of the same type as that used in the ISO 9705 room tests. The composite specimen and backing board were wrapped together in aluminum foil.

The intumescent coating on Material No. 6 did not intumesce fast enough to touch the spark plug prior to ignition. Therefore, this material did not present any specific problems in testing.

Detailed data sheets with the entire Cone calorimeter test results can be found in Appendix C2. In addition, tables (Table 5-1 through 5-9) are provided below for each material with some useful averages. The information in these tables might be helpful in verifying whether the ISO 5660 acceptance criteria proposed by Finland can be supported by the experimental data from this program, or in developing more accurate alternate criteria.

[1] Nitrogen was used to set the zero of the oxygen analyzer. Dry air with an oxygen concentration by volume of 20.95% was used to set the span.

Table 5.1 – Some Useful Cone Calorimeter Data for Material No. 1

	50 kW/m^2		75 kW/m^2		100 kW/m^2	
	Test 1 1348-1	**Test 2**	**Test 1 1348-7**	**Test 2 1488-6**	**Test 1 1358-4**	**Test 2 1498-4**
t_{ig} (s)	324	NI	77	78	17	15
$HRR_{30,max}$ (kW/m^2)	30	--	76	63	60	91
$HRR_{60,max}$ (kW/m^2)	28	--	69	59	59	86
$SPR_{60,max}$ (m^2/s)	0.0058	--	0.0078	0.0063	0.0111	0.0217
SPR_{avg} (m^2/s)	0.0012	--	0.0026	0.0015	0.0032	0.0077
$SEA_{60,max}$ m^2/kg)	174	--	165	121	303	517
SEA_{avg} (m^2/kg)	84	--	65	40	70	240

Table 5.2 – Some Useful Cone Calorimeter Data for Material No. 2

	50 kW/m^2		75 kW/m^2		100 kW/m^2	
	Test 1	**Test 2**	**Test 1 1348-8**	**Test 2 1488-7**	**Test 1 1358-5**	**Test 2 1498-5**
t_{ig} (s)	NI	NI	72	83	13	13
$HRR_{30,max}$ (kW/m^2)	—	--	36	27	43	49
$HRR_{60,max}$ (kW/m^2)	—	—	35	26	42	48
$SPR_{60,max}$ (m^2/s)	—	--	0.0005	0.0007	0.0014	0.0014
SPR_{avg} (m^2/s)	—	—	0.0002	0.0004	0.0004	0.0005
$SEA_{60,max}$ (m^2/kg)	--	—	22	65	45	35
SEA_{avg} (m^2/kg)	--	—	12	29	10	15

Table 5.3 – Some Useful Cone Calorimeter Data for Material No. 3

	25 kW/m^2		50 kW/m^2		75 kW/m^2	
	Test 1 1348-15	**Test 2 1488-1**	**Test 1 1348-3**	**Test 2 1478-3**	**Test 1 1348-9**	**Test 2 1488-2**
t_{ig} (s)	248	250	71	59	25	32
$HRR_{30,max}$ (kW/m^2)	93	94	113	104	125	126
$HRR_{60,max}$ (kW/m^2)	86	93	102	99	115	117
$SPR_{60,max}$ (m^2/s)	0.0896	0.0821	0.1139	0.1025	0.1179	0.1398
SPR_{avg} (m^2/s)	0.0168	0.0185	0.0332	0.0203	0.0273	0.0511
$SEA_{60,max}$ (m^2/kg)	1195	1157	1276	1258	1329	1387
SEA_{avg} (m^2/kg)	792	955	657	531	535	922

Table 5.4 – Some Useful Cone Calorimeter Data for Material No. 4

	25 kW/m^2		50 kW/m^2		75 kW/m^2	
	Test 1 1358-1	**Test 2 1488-2**	**Test 1 1348-4**	**Test 2 1478-5**	**Test 1 1348-10**	**Test 2 1488-10**
t_{ig} (s)	265	355	79	70	35	32
$HRR_{30,max}$ (kW/m^2)	89	104	121	126	154	140
$HRR_{60,max}$ (kW/m^2)	83	99	111	121	145	135
$SPR_{60,max}$ (m^2/s)	0.0833	0.0980	0.1130	0.1306	0.1492	0.1414
SPR_{avg} (m^2/s)	0.0200	0.0221	0.0299	0.0324	0.0473	0.0491
$SEA_{60,max}$ (m^2/kg)	1328	1749	1526	1309	1673	1695
SEA_{avg} (m^2/kg)	1052	1105	713	771	851	1166

Table 5.5 – Some Useful Cone Calorimeter Data for Material No. 5

	50 kW/m^2		75 kW/m^2		100 kW/m^2	
	Test 1 1348-5	**Test 2 1478-6**	**Test 1 1348-1**	**Test 2 1488-11**	**Test 1 1358-6**	**Test 2**
t_{ig} (s)	135	110	58	60	36	
$HRR_{30,max}$ (kW/m^2)	54	75	85	74	84	
$HRR_{60,max}$ (kW/m^2)	50	68	78	62	67	
$SPR_{60,max}$ (m^2/s)	0.0131	0.0181	0.0220	0.0203	0.0249	
SPR_{avg} (m^2/s)	0.0043	0.0083	0.0070	0.0080	0.0057	
$SEA_{60,max}$ (m^2/kg)	304	350	373	406	403	
SE_{avg} (m^2/kg)	306	301	161	276	201	

Table 5.6 – Some Useful Cone Calorimeter Data for Material No. 6

	50 kW/m^2		75 kW/m^2		100 kW/m^2	
	Test 1 1408-27	**Test 2**	**Test 1 1418-3**	**Test 2 1498-1**	**Test 1 1418-5**	**Test 2 1498-6**
t_{ig} (s)	68	NI	30	410	20	22
$HRR_{30,max}$ (kW/m^2)	27	--	77	15	53	54
$HRR_{60,max}$ (kW/m^2)	15	--	77	14	51	27
$SPR_{60,max}$ (m^2/s)	0.0009	--	0.0339	0.0025	0.0133	0.0035
SPR_{avg} (m^2/s)	0.0005	--	0.0096	0.0004	0.0067	0.0038
$SEA_{60,max}$ (m^2/kg)	52	--	1068	102	281	154
SEA_{avg} (m^2/kg)	52	--	391	93	176	154

Table 5.7 – Some Useful Cone Calorimeter Data for Material No. 7

	25 kW/m²		50 kW/m²		75 kW/m²	
	Test 1 1358-3	**Test 2 1488-4**	**Test 1 1348-6**	**Test 2 1478-8**	**Test 1 1348-12**	**Test 2 1498-2**
t_{ig} (s)	1165	690	26	29	14	13
$HRR_{30,max}$ (kW/m^2)	38	34	58	65	46	134
$HRR_{60,max}$ (kW/m^2)	37	33	49	50	41	106
$SPR_{60,max}$ (m^2/s)	0.0029	0.0027	0.0030	0.0053	0.0050	0.0048
SPR_{avg} (m^2/s)	0.0002	0.0005	0.0016	0.0029	0.0019	0.0037
$SEA_{60,max}$ (m^2/kg)	144	207	106	141	87	62
SEA_{avg} (m^2/kg)	64	134	35	62	32	53

Table 5.8 – Some Useful Cone Calorimeter Data for Material No. 8

	25 kW/m²		50 kW/m²		75 kW/m²	
	Test 1 1418-2	**Test 2 1488-5**	**Test 1 1408-28**	**Test 2 1478-9**	**Test 1 1418-4**	**Test 2 1498-3**
t_{ig} (s)	100	145	33	26	16	15
$HRR_{30,max}$ (kW/m^2)	245	288	370	330	451	399
$HRR_{60,max}$ (kW/m^2)	239	257	358	310	444	359
$SPR_{60,max}$ (m^2/s)	0.0850	0.0831	0.1111	0.0964	0.1313	0.1079
SPR_{avg} (m^2/s)	0.0266	0.0262	0.0601	0.0478	0.0766	0.0392
$SEA_{60,max}$ (m^2/kg)	1008	1763	1167	961	1073	979
SEA_{avg} (m^2/kg)	778	766	777	716	727	687

Table 5.9 – Some Useful Cone Calorimeter Data for Material No. 9

	25 kW/m²			50 kW/m²			75 kW/m²		
	Test 1 1708-3	Test 2 1748-1	Test 3 1748-2	Test 1 1708-1	Test 2 1748-3	Test 3 1748-4	Test 1 1708-2	Test 2 1748-5	Test 3 1748-6
t_{ig}	540	420	425	85	105	90	65	55	65
$HRR_{30,max}$	87	91	103	106	120	129	127	152	139
$HRR_{60,max}$	81	82	97	94	108	112	115	129	124
$SPR_{60,max}$	0.0080	0.0103	0.0099	0.0083	0.0114	0.0153	0.0158	0.0218	0.0178
SPR_{avg}	0.0014	0.0009	0.0015	0.0017	0.0022	0.0020	0.0021	0.0038	0.0025
$SEA_{60,max}$	202	234	187	159	392	273	250	351	265
SEA_{avg}	73	58	93	52	78	75	61	111	70

5.5 Cone Calorimeter Conclusions

A quick comparison between the tables in the previous section and the ISO 9705 room test results indicate that the criteria proposed by Finland are quite reasonable, but need some fine-tuning. Material No. 1 failed marginally on smoke in the room/corner test, while the smoke production rate measured in the Cone calorimeter at 50 kW/m^2 was below the limit proposed by Finland. Material No. 2 did very well in the room/corner test, which is consistent with the fact that it did not ignite in the Cone calorimeter at 50 kW/m^2. Material Nos. 3 and 4 performed similarly in the room/corner test, and failed both on heat release rate and smoke production. The Cone calorimeter data at 50 kW/m^2 are comparable for these two materials, and consistent with the room tests performance (except for perhaps the ignition time). Material No. 5 also failed in the room/corner test, but performed significantly better than Material Nos. 3 and 4. This is probably what one would conclude from the Cone calorimeter data as well. Material No. 6 (coated version of Material No. 5) failed marginally on smoke, while this is not identified as a problem on the basis of the Cone calorimeter data. Material No. 7 did well in the room/corner test and the Cone calorimeter, except for the ignition time, which is slightly below the 30-second limit proposed by Finland. The fact that this material is relatively easy to ignite is probably not very important because is shrinks away from the fire in the room so that the incident heat flux is greatly reduced from that in the Cone calorimeter. Moreover, since it is a thin finish material, the amount of energy that can be released following ignition is rather minimal. Material No. 8 is clearly the poorest performer in both the room/corner test and the Cone calorimeter. Finally, one would expect on the basis of the Cone calorimeter data, that room/corner test performance of Material No. 9 (at least in terms of heat release rate, smoke production is of course significantly lower) is comparable to that of Materials Nos. 3 and 4. In reality, Material No. 9 performed significantly better. This preliminary and qualitative comparison between Cone calorimeter and room/corner test data seems to indicate that it may be feasible to develop accurate ISO 5660 acceptance criteria for fire-restricting materials. This issue will be revisited in more detail in Section 8.

6.0 IMO SURFACE FLAMMABILITY TESTS

6.1 Introduction

All lining materials were tested in accordance with IMO Resolution A.653 "Recommendation on Improved Fire Test Procedures for Surface Flammability of Bulkhead, Ceiling and Deck Finish Materials." The test procedure is comparable to ASTM Standard E 1317-97a, entitled "Standard Test Method for Flammability of Marine Surface Finishes." The test procedure is used to measure fire characteristics of bulkhead, ceiling, and deck finish materials as a basis for characterizing their flammability and, thus, their suitability for use in marine construction. The results of the test, including a number of flame spread and heat release parameters are evaluated against established criteria in SOLAS, as referenced in the FTP code.

6.2 IMO Surface Flammability Test

6.2.1 Test Setup

The apparatus, calibration procedure, and test protocol are described in detail in IMO Resolution A.653(16). The flame spread apparatus is used primarily for determining the surface burning characteristics of wall and ceiling materials. The burning characteristics are determined by heat release and flame front propagation measurements.

Apparatus - The apparatus consists of a radiant panel having dimensions of 280 x 483 mm, mounted vertically, making an angle of 15° with the specimen. The panel is fueled by a mixture of natural gas and air, the flow of which controls the incident flux to the sample. The orientation of the panel results in an incident irradiance that decreases from 50 kW/m^2 at one end to approximately 1 kW/m^2 at the other end of the specimen. A schematic of the test setup is shown in Figure 6.1.

Figure 6.1 – Schematic of the IMO Surface Flammability Test Apparatus

Specimen – The sample is vertically oriented, and has dimensions of 155 x 800 mm. The back surface and edges of the sample are wrapped using a single piece of 0.02-mm aluminum foil (see Figure 1 of Appendix D1). The wrapped sample is placed in a specimen holder, and backed by a 10 ± 2-mm thick piece of noncombustible insulating material (see Figure 2 of Appendix D2). The backing material chosen for this test series was Promatect® H, which had a nominal density of 750 kg/m^2. This material was chosen for consistency with ISO 9705, ISO 5660, and the IMO Smoke and Toxicity (Part 2 of the IMO Fire Test Procedure) tests conducted in this program.

Pilot – The sample is ignited by a non-impinging, acetylene/air pilot flame. The pilot is placed at the "hot" end of the specimen. If the sample fails to ignite, appropriations are made in the standard to incorporate an impinging pilot, directed at the top-half of the sample. Once ignited, flame spread is monitored by aligning markings on the sample with viewing rakes placed at 50-mm spacings along the specimen.

Fume Stack – Hot gases resulting from sample combustion are vented through a fume stack, instrumented with a thermopile. The thermopile records the temperature of the hot gases, and is compensated for the stack wall temperature. The compensated signal is converted to an equivalent heat release through a function derived during gas burner calibrations.

6.2.2 Calibration Procedure

The calibration procedure is outlined in Appendix 4 of IMO A.653, and Appendix A1.3 of ASTM E 1317. The calibration procedure involves three major checks: thermal adjustment of panel operating level, compensation adjustment, and fume stack calibration. These checks are performed on a monthly basis, and were last conducted at the commencement of this test program.

Thermal Adjustment of Panel Operating Levels – A thermal adjustment of panel operating levels is made to ensure the proper irradiance profile on a sample. The procedure is described in IMO A.653 Appendix 4.3, and similarly described in ASTM E 1317, Appendix A1.3. To conduct this calibration, a dummy specimen, having the same lateral dimensions as a test specimen, is mounted into a specimen holder. The dummy specimen is fabricated from a 20-mm thick Promatect® H insulation board, having a density of 800 ± 100 kg/m^3. The dummy specimen accepts a fluxmeter at several locations along the centerline of the dummy specimen (see Appendix D1, Figure 3). The irradiance levels at 50 and 350 mm are fixed to standard values, and the irradiance level at other locations on the specimen are checked for agreement with the published irradiance profile. The fluxes at the 50- and 350-mm distances are adjusted using varying fuel-gas ratios to the panel. Once the profile has been established, the fuel/air ratio is not changed.

Compensation Adjustment – Compensation adjustment was done in accordance with IMO A.653 Appendix 4.5 and similarly ASTM E 1317 Appendix A1.3.5. Compensation of the thermopile measurement is achieved by subtracting a fraction of the generated electrical signal from the stack thermocouples (thermopile). The purpose of the adjustment is to eliminate, as far as practical, from the stack signal the long-term signal changes resulting from the relatively slow stack metal temperature variations.

Compensation is attained through the measurement of stack response to a thermal pulse (typically on the order of 1-7 kW). The thermal pulse is induced by the rapid placement and subsequent extinguishment of a methane burner (see Figure 4 of Appendix D1). Compensation is adjusted such that the response to a 7-kW fire source does not overshoot the steady value by more than seven percent. The adjustment of compensation is also used to improve the response time of the stack (time to reach a maximum value, as a result of a thermal pulse).

Fume Stack Calibration – Fume stack calibration was done in accordance with IMO A.653 Appendix 4.6 and similarly ASTM E 1317 Appendix A1.3.6. The goal of the fume stack calibration is the generation of a function relating heat release of a sample to stack millivolt output. This is done by introducing the methane burner used for compensation adjustment, with varying methane flows, i.e., varying heat release. A curve is generated depicting different millivolt responses to the heat releases under the fume stack. This procedure is repeated with the methane burner at the hot and cold ends of the apparatus, ensuring similar stack response to heat release at both locations.

6.2.3 Test Procedure

The test apparatus is brought to operating conditions, as measured by the fluxmeter installed at the 350-mm location of the dummy specimen. The flux at the 350-mm position should be within two percent of the calibration flux at this position.

With the pilot lit, stack signal and fluxmeter output are monitored for stability. Once the signals are stabilized, the data acquisition system is started, and the stack signal baseline is recorded for a period of three minutes. Immediately following the three-minute baseline, the fluxmeter and dummy specimen are removed from the apparatus and replaced by a prepared sample, mounted in a specimen holder. The test clock is started, and once inserted, observations of ignition times, and flame spread along the sample are made (see Figure 5 of Appendix D1). The test is terminated with the occurrence of any of the following conditions: the specimen fails to ignite after ten minutes of exposure, three minutes have passed since all flaming from the specimen has ceased, or flaming reaches the end of the specimen and ceases.

The test is conduced on three identical samples. In the event that a sample fails to ignite, an additional test utilizing an impinging pilot is conducted to promote ignition.

6.2.4 Results

The results obtained from the test consist of a set of five derived flammability characteristics, with four of the characteristics contributing to the pass/fail criteria. Surface burning characteristics used in the evaluation of a material include the following:

Heat for Ignition (HFI) – The heat for ignition is defined as the product of the time for the flame front to reach the 150-mm location and the flux at the 150-mm position. The flux used is the value obtained during the calibration of the panel operating levels. This parameter is described in Section 3.6 of IMO A.653, but is not part of the performance criteria specified in Section 10 of the standard.

Critical Flux at Extinguishment (CFE) – The critical flux at extinguishment is defined as the flux level at the specimen surface corresponding to the distance of furthest advance and subsequent self-extinguishment of the flame front on the centerline of the sample. The flux reported is based on calibration tests with a dummy specimen.

Heat for Sustained Burning (Q_{sb}) – The heat for sustained burning is defined as the product of time from initial specimen exposure until the arrival of the flame front, and the incident flux level at that same location as measured with a dummy specimen during calibration. The average heat for sustained burning is calculated using the Q_{sb} values from 150 mm to either the final station or the 400-mm station, whichever produces the lower value.

Total Heat Release (Q_t) – The millivolt stack signal is converted to a corresponding heat release through the use of a function derived in the fume stack calibration procedure. The heat release is given by integration of the positive part of the heat release rate curve.

Peak Heat Release Rate (q_p) – The peak heat release, the maximum heat release rate observed during the test period, is also derived from the stack millivolt output data.

General Performance Criteria – The performance criteria specified in IMO A.653 originated from requirements in II-2/3.8, II-2/34, and I-2/49 of SOLAS 1974. The surface flammability criteria are presented in Section 10 of the IMO Resolution, and include a separate set of performance criteria for bulkhead, wall and ceiling linings, and floor coverings. The criteria are summarized in Table 6.1.

Table 6.1 – Surface Flammability Criteria

Bulkhead, Wall, and Ceiling Linings				Floor Coverings			
CFE (kW/m^2)	**Q_{sb} (MJ/m^2)**	**Q_t (MJ)**	**q_p (kW)**	**CFE (kW/m^2)**	**Q_{sb} (MJ/m^2)**	**Q_t (MJ)**	**q_p (kW)**
≥ 20.0	≥ 1.5	≤ 0.7	≤4.0	≥7.0	≥ 0.25	≤ 2.0 *	≤ 10.0

10. Original value in IMO Resolution A.653(16) is 1.5 MJ, modified to 2 MJ in the FTP Code.

6.3 Calibration Data

Calibrations were performed in accordance with IMO Appendix 4.3, 4.5, and 4.6, and as described in Section 6.2 of this report.

6.3.1 Thermal Adjustment of Panel Operating Levels

Panel fuel and air flow rates were adjusted until an acceptable flux level was recorded at the 50-mm mark. Once established, the flux pattern was measured. The resulting curve is shown graphically in Figure 6.2.

Figure 6.2 – Heat Flux Profile as a Result of Thermal Adjustment of Panel Operating Levels

The flux distribution shows good agreement with the published 50- and 350-mm flux levels. Both the 50- and 350-mm fluxes could not be matched simultaneously, since the two fluxes are not independent. The resulting profile is within 4% of both the 50- and 350-mm published flux values. The remaining positions are within 8.1% of the standard values (Figure 6.2 shows ± 10% error bars).

A 13.6% discrepancy was noted at the 650-mm position. This percent deviation represented a difference of 0.42 kW/m^2 between measured and standard values. This could be attributed to unstable convective flows in this region of the dummy specimen.

6.3.2 Compensation Adjustment

A 7-kW thermal pulse was imposed on the stack by burning a prescribed flow rate of methane through a standard line burner. The millivolt output of the stack was monitored. This procedure was repeated with subsequent adjustments to the compensation resistor. The final setting of 57.5% compensation yielded an acceptable response time with less than 7% signal drift from the steady output reached after six minutes. This compensation reflected optimal response and drift characteristics for the fume stack. The stack output is shown graphically in Figure 6.3.

Figure 6.3 – Stack Response to a 7 kW Thermal Pulse

The time to reach a maximum signal output is on the order of 1.5 – 1.76 minutes, slightly slower than the one-minute response time depicted graphically in the standard. A potential reason for the slow response may be attributed to the thermal mass present in the stack design itself. The materials which form the stack are specified on the official IMO drawing as 0.046 ± 0.005 mm. The stack used for the IMO surface flammability testing was measured and had a thickness of 0.050 mm. Although the stack thickness was within the tolerances specified by IMO, the effect of the added mass on the response and cool-down times is a question.

6.3.3 Fume Stack Calibration

A fume stack calibration was conducted by introducing known heat releases via a line burner, and measuring stack millivolt output. This process was repeated for six heat release rate levels, and a curve (Figure 6.4) was generated.

The second order polynomial was used to convert stack output (Mv) to a sample heat release (kW).

Figure 6.4 – Heat Input versus Stack Response

6.4 Test Results

All materials were tested for surface flammability in accordance with IMO Resolution A.653. As required by the IMO procedure, three tests were conducted, and an average of the results from the three tests is compared to the pass/fail criteria. For ease of presentation, a summary of the results for each material is presented in this section, with complete data from each run presented in Appendix D2.

6.4.1 Material No. 1 IMO Surface Flammability Test Results

Material No. 1 did not ignite during the first two tests. As a result, an impinging pilot was used for the third test. The sample did not ignite, even in the presence of the impinging pilot. The material passed all the performance requirements.

6.4.2 Material No. 2 IMO Surface Flammability Test Results

Material No. 2 did not ignite during the first three tests. As a result, an impinging pilot was used for the fourth test. The sample did not ignite, even in the presence of the impinging pilot. The material passed all the performance requirements.

6.4.3 Material No. 3 IMO Surface Flammability Test Results

Material No. 3 exhibited a degree of bubbling at the sample surface and slight discoloration prior to ignition. The samples also had a tendency for re-ignition once flames were out; however, flame propagation after the initial stages was minimal. Three tests were conducted, with a summary of results presented in Table 6.2 below.

Table 6.2 – Summary of IMO Surface Flammability Results for Material No. 3

Critical Flux at Extinguishment	23.16 kW/m^2
Heat for Sustained Burning	4.33 MJ/m^2
Heat for Ignition	3.75 MJ/m^2
Total HR	1.04 MJ
Peak HRR	1.83 kW
Extinguishment Location	400 mm
Extinguishment Time	1162 seconds

Material No. 3 failed to meet the criteria for total heat release specified in the resolution. The value of 1.04 MJ was greater than the allowable 0.7 MJ.

6.4.4 Material No. 4 IMO Surface Flammability Test Results

Material No. 4 exhibited a similar degree of bubbling to Material No. 3. Material No. 4 also had a tendency to drip resin from the front face of the sample. This phenomenon was noted at approximately 420 seconds into the first test, with similar behavior noted during Tests 2 and 3. A summary of results of the three tests is presented in Table 6.3.

Table 6.3 – Summary of IMO Surface Flammability Results for Material No. 4

Critical Flux at Extinguishment	23.16 kW/m^2
Heat for Sustained Burning	4.54 MJ/m^2
Heat for Ignition	4.36 MJ/m^2
Total HR	1.21 MJ
Peak HRR	2.47 kW
Extinguishment Location	397 mm
Extinguishment Time	1240 seconds

Material No. 4 failed to meet the criteria for total heat release specified in the resolution. The value of 1.21 MJ was greater than the allowable 0.7 MJ.

6.4.5 Material No. 5 IMO Surface Flammability Test Results

A total of four tests were conducted for Material No. 5, since the third test of the series failed to ignite with steady flames. In general, all tests produced only weak ignition with oscillating flames. Tests 1, 2, and 4 were used to present an average for the material. A summary of results is presented in Table 6.4.

Table 6.4 – Summary of IMO Flame Spread Results for Material No. 5

Critical Flux at Extinguishment	39.64 kW/m^2
Heat for Sustained Burning	8.09 MJ/m^2
Heat for Ignition	9.01 MJ/m^2
Total HR	0.04 MJ
Peak HRR	0.31 kW
Extinguishment Location	255 mm
Extinguishment Time	386 seconds

Material No. 5 met all the performance criteria for surface flammability. The material exhibited only brief ignition with only oscillating flame front propagation.

6.4.6 Material No. 6 IMO Surface Flammability Test Results

A total of two tests were conducted for Material No. 6. The material failed to ignite during the first test of the series, and subsequently failed to ignite during the second test, in the presence of an impinging pilot flame. The intumescence of the sample was sufficient to prevent ignition. Since Material No. 6 is similar in nature to Material No. 5, the lack of ignition in Material No. 6 was expected. The material passed all the performance requirements, since it failed to ignite.

6.4.7 Material No. 7 IMO Surface Flammability Test Results

A total of two tests were conducted on Material No. 7, since the behavior of the sample did not allow for accurate reporting of flame spread characteristics. The material (a wall covering over a noncombustible substrate) melted rapidly (approximately 20 seconds into the exposure), exposing the noncombustible substrate. Once exposed, the noncombustible substrate did not support ignition. The second test of the series was conducted in the presence of an impinging pilot, with no ignition on the sample. The material passed all the performance requirements, since it failed to ignite; however, its failure to ignite was due to the physical reaction of the covering/substrate to the radiant panel.

6.4.8 Material No. 8 IMO Surface Flammability Test Results

A total of three tests were conducted for Material No. 8. In general, all tests produced normal burning behavior, with ignition occurring following a rapid bubbling and charring of the sample surface. Flame progress was steady. A summary of results is presented in Table 6.5 below.

Table 6.5 – Summary of IMO Surface Flammability Results for Material No. 8

Critical Flux at Extinguishment	11.65 kW/m^2
Heat for Sustained Burning	2.10 MJ/m^2
Heat for Ignition	1.91 MJ/m^2
Total HR	2.00 MJ
Peak HRR	6.11 kW
Extinguishment Location	510 mm
Extinguishment Time	1060 seconds

Material No. 8 failed on three of the four performance criteria for surface flammability (passed on heat for sustained burning threshold).

6.4.9 Material No. 9 IMO Surface Flammability Test Results

A total of three tests were conducted for Material No. 9. In general, the burning behavior of Material No. 9 was similar to that of Material No. 8. Resins were almost completely consumed during the test, such that only fibrous media remained following the test. Flame progress was steady. A summary of results is presented in Table 6.6.

Material No. 9 failed on two out of the four performance criteria for surface flammability (passed on heat for sustained burning and peak heat release rate).

Table 6.6 – Summary of IMO Surface Flammability Results for Material No. 9

Critical Flux at Extinguishment	17.69 kW/m^2
Heat for Sustained Burning	5.09 MJ/m^2
Heat for Ignition	4.72 MJ/m^2
Total HR	1.18 MJ
Peak HRR	2.62 kW
Extinguishment Location	457 mm
Extinguishment Time	1617 seconds

6.5 IMO Surface Flammability Conclusions

Since materials tested under the IMO Resolution can be quantified as pass or fail, Table 6.7 summarizes the results, with failing criteria highlighted in bold.

Table 6.7 – IMO Flame Spread Results Summary

Parameter	Material				
	3	**4**	**5**	**8**	**9**
Critical Flux at Ext. (CFE) [kW/m^2]	23.16	23.16	39.84	**11.65**	**17.69**
Heat for Sustained Burning (Q_{sb}) [MJ/m^2]	4.33	4.54	8.09	2.10	5.09
Heat for Ignition (Q_{ig}) [MJ/m^2]	3.75	4.36	9.01	1.91	4.72
Total HR (Q_t)[MJ]	**1.04**	**1.21**	0.04	**2.00**	**1.18**
Peak HRR (q_p) [kW]	1.83	2.47	0.31	**6.11**	2.62
Extinguishment Location (X_e) [mm]	400	3.97	255	510	457
Extinguishment Time (t_e) [seconds]	1162	1240	386	1060	1617
Met All Criteria	**No**	**No**	Yes	**No**	**No**

As mentioned earlier, Material Nos. 1, 2, 6, and 7 were considered to have passed the IMO surface flammability test, as they failed to ignite.

7.0 LATERAL IGNITION AND FLAME SPREAD TESTING

7.1 Introduction

Materials were tested to determine ignition and flame spread properties in accordance with ASTM E 321-97-a, "Standard Test Method for Determining Material Ignition and Flame Spread Properties." The test method is also referred to as the Lateral Ignition and Flame Spread Test or LIFT. The test procedure generates material properties used in fire models of fire growth and flame spread over solid surfaces.

The test protocol involves two procedures: one for determining the ignition parameters of the material, and one for obtaining opposed flow flame spread properties. The first procedure measures time to ignition at different heat flux levels and the critical heat flux for piloted ignition. The second procedure consists of experiments to obtain the lateral flame spread rate over a long specimen exposed to a decreasing heat flux field.

7.2 Lateral Ignition and Flame Spread Test

The LIFT method incorporates two separate test procedures: an ignition test protocol and a flame spread test protocol. The apparatus and sample preparation procedure are similar to those described in Section 6.2. Details for each of the two test procedures are also provided here.

7.2.1 Test Setup

The apparatus used for the LIFT procedure is similar to that used for IMO Surface Flammability testing described in Section 6.2.1.

Apparatus **—** The apparatus is identical to that described in Section 6.2.1, incorporating an angled radiant panel, fueled by a mixture of natural gas and air.

Ignition Sample Preparation — The ignition specimens have dimensions of 155 x 155 mm. Ignition samples used in this program were backed with a noncombustible insulation board, with a thickness of 12 mm and a density of 750 ± 100 kg/m³. The substrate was chosen for consistency with other phases of testing in this program. The ignition sample is placed over the substrate and wrapped in a single sheet of 0.02-mm thick, aluminum foil (see Figure 1 in Appendix E1). The wrapped sample is placed at the "hot" end of a specimen holder. Spacers are used at the "cold" end of the specimen to account for the thickness of the specimen and substrate. The ignition sample is backed by a 155 x 800-mm piece of insulating backing board, having a thickness of 25 mm and a nominal density of 200 ± 50 kg/m³.

Flame Spread Sample Preparation — The flame spread sample has dimensions of 155 x 800 mm, and is prepared in a manner similar to the ignition sample. A specimen is placed over a noncombustible substrate, and wrapped with a single sheet of aluminum foil, covering the back and edges of the sample (see Figure 3 in Appendix E1). The sample is then placed in the specimen holder, and followed by a 155 x 800-mm piece of insulating, backing board, having a thickness of 25 mm, and a nominal density of 200 ± 50 kg/m³.

Pilot — The pilot assembly used in the testing is a horizontally oriented, non-impinging gas flame. The pilot is fueled by an acetylene/air mixture, and is placed above the sample at the hot end of the specimen. The pilot flame length is on the order of 180 mm, and burns parallel to a flange mounted atop the specimen holder. The flange has dimensions of 180 x 75 mm, and is designed to provide a solid boundary guiding hot gasses generated by the sample over the pilot flame (see Figure 5 in Appendix E1).

7.2.2 Calibration Procedure

The calibration of the apparatus is focused on the thermal adjustment of the radiant panel operating level. This procedure involves verifying the flux profile imposed on a dummy specimen, and adjusting the panel fuel/air mixture until a standard profile is achieved. The procedure is described in further detail in Section 6.2.2.

7.2.3 Test Procedure

The test procedure described in ASTM E 1321 is divided into two separate procedures: ignition testing and flame spread testing.

Ignition Test Procedure — The ignition test procedure is intended to bracket the critical flux to ignition of a material, while providing ignition time measurements over a range of heat fluxes between the critical level and the maximum level that the apparatus is capable of producing.

A specific flux is generated by the radiant panel, as measured by a fluxmeter located at 50 mm from the hot end of the sample. The pilot is ignited, and the flux at the 50-mm location is monitored. Once the heat flux is steady, the ignition specimen is inserted, and time to ignition is recorded.

This procedure was repeated for varying levels of flux. Times to ignition were recorded at 10 kW/m^2 intervals from 62 kW/m^2 (the panel's maximum output) to 30 kW/m^2. At fluxes lower than 30 kW/m^2, a 5-kW/m^2 interval was used. Once a flux range for ignition was defined, fluxes were changed in 2-kW/m^2 intervals until the critical flux for ignition was determined.

Flame spread Test Procedure — The flame spread test is conducted at a flux level which is between 5 and 10 kW/m^2 greater than the critical flux for ignition. The panel is brought to these operating conditions and verified through the use of a fluxmeter at the 50-mm location. The sample is inserted and preheated in the absence of a pilot burner for a period of time determined through ignition testing (see Section 7.2.4). Following the preheat time, the pilot is lit and the test clock is started. Observations of flame spread distance and corresponding times are recorded. The test is concluded when either the flame front self extinguishes or reaches the end of the sample. The times to extinguishment and maximum flame front travel are recorded.

7.2.4 Test Results

Test results from ignition testing are used in the calculation of parameters for flame spread testing.

Ignition Test Results— The results from ignition testing include the critical flux for ignition, and a time-to-ignition versus incident flux profile. From this profile, a linearized function can be established relating normalized incident flux to the square root of time (t) (See Appendix E2 for examples of test data.). The slope of this line (b), a preheat time (t*), ignition temperature (T_{ig}), and material properties ($k\rho c$) are determined using the calculation procedures specified in Section 12.1 of the ASTM E 1321.

Flame Spread Test Results — The results of flame spread testing include an array of flame front distances and respective times to reach that distance. These data are analyzed as specified in Section 12.2 of the ASTM Standard to yield a flame front velocity ©, ignition flux ($\dot{q}''_{o,ig}$), minimum flux for spread ($\dot{q}''_{o,s}$), minimum temperature for spread ($T_{s,min}$), and a flame front parameter (Φ).

7.3 Calibration Data

As mentioned in Section 7.2.2, the calibration procedure verifying the proper flux profile was completed as part of the calibration for IMO Surface Flammability testing, with results of the calibration appearing in Section 6.3.1.

7.4 Test Results

All nine materials were tested in accordance with the ignition test procedure. Once bracketed, the critical flux for ignition ($\dot{q}''_{o,ig}$) was reported as 1 kW/m² less than the lowest flux for ignition. As a result of ignition test results, several materials were not tested for flame spread on the basis of their failure to ignite at high flux levels during ignition testing.

A subset of materials tested using the ASTM E 1321 test procedure generated very poor flame spread data. Since in some cases, there was insufficient test data generated from testing under the ASTM E 1321 protocol to calculate flame spread parameters, flame spread data from IMO A.653/ASTM E 1317 testing was analyzed in accordance with the ASTM E 1321 procedure to generate flame spread parameters. The following sections present the ignition data, flame spread characteristics based on ASTM E 1321 test data, as well as flame spread characteristics based on IMO A.653/ASTM E 1317 test data for comparison.

A summary of each material is presented in the respective sections, with complete data sheets presented in Appendices E2 and E3.

7.4.1 Material 1 Test Results

Ignition Results **–** Material 1 failed to ignite under a flux of 61.9 kW/m^2 (the panel's maximum operating flux). This precluded flame spread testing of the material.

7.4.2 Material 2 Test Results

Ignition Results **–** Material 2 failed to ignite under a flux of 61.7 kW/m^2 (the panel's maximum operating flux). This precluded flame spread testing of the material.

7.4.3 Material 3 Test Results

Ignition Results **–** Material 3 exhibited good ignition properties. A total of nine ignition tests were performed on the material, producing the following ignition characteristics, summarized in Table 7.1.

Table 7.1 – Ignition Test Results for Material 3

Critical Ignition Flux ($\dot{q}''_{o,ig}$)	14.9 kW/m²
Ignition Temperature (T_{ig})	375°C
Slope (b)	0.0369 1√s
Pre-heat Time (t*)	735 s
kρc	1.65 (kW/m²K)² s
Surface Heat Transfer Coef. (h)	41.99 W/m²K

ASTM Flame Spread Test Results – Two of the three flame spread tests conducted using the ASTM E 1321 procedure produced reportable flame spread data. From the two tests conducted, the flame spread data in Table 7.2 were obtained using the calculation procedures in ASTM E 1321.

Table 7.2 – Flame Spread Properties of Material 3, Based on ASTM Flame Spread Tests

Flame Spread Parameter ©	0.22 m²√s/kW √mm
Critical Ignition Flux ($\dot{q}''_{o,ig}$)	19.0 kW/m²
Minimum Flux for Spread ($\dot{q}''_{o,s}$)	12.83 kW/m²
Minimum Temperature for Spread ($T_{s,min}$)	325°C
Flame Heating Parameter (Φ)	19.47 (kW/m)²/m

IMO Flame Spread Test Results – Three of the IMO tests produced flame-spread data which were reportable. These data were analyzed in accordance with the procedures in ASTM E 1321 yielding the results summarized in Table 7.3.

Table 7.3 – Flame Spread Properties of Material 3, Based on IMO Flame Spread Tests

Flame Spread Parameter ©	0.44 $m^2\sqrt{s}/kW\sqrt{mm}$
Critical Ignition Flux ($\dot{q}''_{o,ig}$)	15.8 kW/m^2
Minimum Flux for Spread ($\dot{q}''_{o,s}$)	16.24 kW/m^2
Minimum Temperature for Spread ($T_{s,min}$)	406°C
Flame Heating Parameter (Φ)	4.79 $(kW/m)^2/m$

7.4.4 Material 4 Test Results

Ignition Results – Material 4 exhibited good ignition properties. A total of nine ignition tests were performed on the material, producing the following ignition characteristics summarized in Table 7.4.

Table 7.4 – Ignition Test Results for Material 4

Critical Ignition Flux ($\dot{q}''_{o,ig}$)	14.5 kW/m^2
Ignition Temperature (T_{ig})	370°C
Slope (b)	0.0340 $1/\sqrt{s}$
Pre-heat Time (t*)	864 s
kρc	1.89 $(kW/m^2K)^2$ s
Surface Heat Transfer Coef. (h)	41.48 W/m^2K

ASTM Flame Spread Test Results – One of the three flame spread tests using the ASTM E 1321 procedure produced reportable flame spread data, due to the erratic nature of the burning characteristics of the material following the pre-heat. As summarized in Table 7.5, flame spread data based on the single test were obtained using the calculation procedures in ASTM E 1321.

Table 7.5 – Flame Spread Properties of Material 4, Based on ASTM Flame Spread Tests

Flame Spread Parameter ©	0.42 $m^2\sqrt{s}/kW\sqrt{mm}$
Critical Ignition Flux ($\dot{q}''_{o,ig}$)	21.7 kW/m^2
Minimum Flux for Spread ($\dot{q}''_{o,s}$)	16.94 kW/m^2
Minimum Temperature for Spread ($T_{s,min}$)	428°C
Flame Heating Parameter (Φ)	6.26 $(kW/m)^2/m$

IMO Flame Spread Test Results – Three of the IMO tests conducted produced flame spread data which were reportable. These data were analyzed in accordance with the procedures in ASTM E 1321 yielding the following results summarized in Table 7.6.

Table 7.6 – Flame Spread Properties of Material 4, Based on IMO Flame Spread Tests

Flame Spread Parameter ©	0.24 $m^2\sqrt{s}/kW\sqrt{mm}$
Critical Ignition Flux ($\dot{q}''_{o,ig}$)	16.5 kW/m^2
Minimum Flux for Spread ($\dot{q}''_{o,s}$)	16.55 kW/m^2
Minimum Temperature for Spread ($T_{s,min}$)	419°C
Flame Heating Parameter (Φ)	18.37 $(kW/m)^2/m$

7.4.5 Material 5 Test Results

Ignition Results – A total of seven ignition tests were performed on the material. In general, what ignition was noted for Material 5, could not be characterized as strong ignition. In many cases, ignition comprised of oscillating flames. In one case, the ignition time was recorded as 1032 seconds at a flux level of 22.8 kW/m^2. When plotted, this point represented an outlier and was not used in further calculations (see Appendix E2). The remaining ignition data produced the following ignition characteristics summarized in Table 7.7.

Table 7.7 – Ignition Test Results for Material 5

Ignition Flux ($\dot{q}''_{o,ig}$)	17.2 kW/m²
Ignition Temperature (T_{ig})	453°C
Slope (b)	0.0432 1/√s
Pre-heat Time (t*)	536 s
kρc	1.73 (kW/m²K)² s
Surface Heat Transfer Coef. (h)	50.39 W/m²K

ASTM Flame Spread Test Results– Ignition did not occur in either of two flame spread tests conducted. Tests were conducted at a flux level of approximately 27.8 kW/m². The second test was conducted with a pilot directed at the sample in an effort to ignite the sample. Ignition did not occur, thus, no flame spread characteristics could be derived from the tests.

IMO Flame Spread Test Results – Ignition did not occur in either of two IMO flame spread tests conducted even in the presence of an impinging pilot. Hence, flame spread data for Material 5 could not be obtained.

7.4.6 Material 6 Test Results

Ignition Results – Two ignition tests were performed on the material. The intumescence of Material 6 made it difficult to ascertain surface ignition. In the two cases reported, attached flames were observed at the edge of the sample. The ignition data from the two reportable tests produced the following ignition characteristics summarized in Table 7.8.

Table 7.8 – Ignition Test Results for Material 6

Ignition Flux ($\dot{q}''_{o,ig}$)	48.8 kW/m²
Ignition Temperature (T_{ig})	643°C
Slope (b)	0.0313 1/√s
Pre-heat Time (t*)	1024 s
kρc	8.00 (kW/m²K)² s
Surface Heat Transfer Coef. (h)	78.38 W/m²K

ASTM Flame Spread Test Results – Ignition did not occur during the flame-spread test conducted. The test was conducted at a flux level of approximately 57.8 kW/m², with a pilot directed at the sample in an effort to ignite the sample. Ignition did not occur, thus, no flame spread characteristics could be derived from the test.

IMO Flame Spread Test Results – Ignition did not occur in either of two IMO flame spread tests conducted, even in the presence of an impinging pilot. Hence, flame spread data for Material 6 could not be obtained.

7.4.7 Material 7 Test Results

Ignition Results – A total of three ignition tests were performed on the material. The physical reaction of the material made it difficult to ascertain ignition properties. As described in Section 6.4.7, the material's reaction to the radiant flux caused the covering of the material to melt and retreat, exposing the noncombustible substrate. The result was a surface which failed to ignite. The ignition reported in the three tests was limited to ignition in the corners of the ignition sample, where portions of the covering remained. Although ignition data were recorded, the nature of the ignition was outside the intent of the standard. Nonetheless, the ignition data produced the following ignition characteristics summarized in Table 7.9.

Table 7.9 – Ignition Test Results for Material 7

Ignition Flux ($\dot{q}''_{o,ig}$)	49.7 kW/m²
Ignition Temperature (T_{ig})	647°C
Slope (b)	0.1733 1/√s
Pre-heat Time (t*)	33 s
kρc	0.27 (kW/m²K)² s
Surface Heat Transfer Coef. (h)	79.22 W/m²K

ASTM Flame Spread Test Results – Drawing upon prior behavior of the sample, flame spread tests were not conducted.

IMO Flame Spread Test Results – The material failed to ignite during the two IMO flame spread tests conducted. Hence, no flame-spread characteristics could be determined.

7.4.8 Material 8 Test Results

Ignition Results – A total of eight ignition tests were performed on the material. Ignition of this material was clear and easily reported. The ignition data produced the following ignition characteristics summarized in Table 7.10.

Table 7.10 – Ignition Test Results for Material 8

Ignition Flux ($\dot{q}''_{o,ig}$)	12.2 kW/m²
Ignition Temperature (T_{ig})	337°C
Slope (b)	0.0505 1/√s
Pre-heat Time (t*)	392 s
kρc	0.74 (kW/m²K)² s
Surface Heat Transfer Coef. (h)	38.48 W/m²K

ASTM Flame Spread Test Results – Three flame spread tests conducted using the ASTM E 1321 procedure produced reportable flame spread data. Tests 2 and 3 of the series included flame spread times at the last station which represented outliers when plotted. These times (Test 2- 511 seconds and Test 3 – 594 seconds) were excluded from the calculation of flame spread characteristics. From tests conducted, the flame spread characteristics summarized in Table 7.11could be obtained using the calculation procedures in ASTM E 1321.

Table 7.11 – Flame Spread Properties of Material 8, Based on ASTM Flame Spread Tests

Flame Spread Parameter (C)	0.16 m²√s/kW √mm
Critical Ignition Flux ($\dot{q}''_{o,ig}$)	15.3 kW/m²
Minimum Flux for Spread ($\dot{q}''_{o,s}$)	8.27 kW/m²
Minimum Temperature for Spread ($T_{s,min}$)	234°C
Flame Heating Parameter (Φ)	19.11 (kW/m)²/m

IMO Flame Spread Test Results – Three of the IMO tests conducted produced flame spread data which were reportable. These data were analyzed in accordance with the procedures in ASTM E 1321 yielding the results summarized in Table 7.12.

Table 7.12 – Flame Spread Properties of Material 8, Based on IMO Flame Spread Tests

Flame Spread Parameter (C)	0.16 $m^2\sqrt{s}/kW\sqrt{mm}$
Critical Ignition Flux ($\dot{q}''_{o,ig}$)	19.1 kW/m^2
Minimum Flux for Spread ($\dot{q}''_{o,s}$)	6.04 kW/m^2
Minimum Temperature for Spread ($T_{s,min}$)	177°C
Flame Heating Parameter (Φ)	18.92 $(kW/m)^2/m$

7.4.9 Material 9 Test Results

Ignition Results – A total of eight ignition tests were performed on the material. Ignition of this material was similar to that of Material 8, and was clear and easily reported. The ignition data produced the ignition characteristics summarized in Table 7.13.

Table 7.13 – Ignition Test Results for Material 9

Ignition Flux ($\dot{q}''_{o,ig}$)	15.7 kW/m^2
Ignition Temperature (T_{ig})	385°C
Slope (b)	0.0370 $1/\sqrt{s}$
Pre-heat Time (t*)	732 s
$k\rho c$	1.72 $(kW/m^2K)^2$ s
Surface Heat Transfer Coef. (h)	43.01 W/m^2K

ASTM Flame Spread Test Results–Three flame spread tests conducted using the ASTM E 1321 procedure produced reportable flame spread data. From tests conducted, the flame spread characteristics summarized in Table 7.14 were obtained using the calculation procedures in ASTM E 1321.

Table 7.14 – Flame Spread Properties of Material 9, Based on ASTM Flame Spread Tests

Flame Spread Parameter (C)	0.17 $m^2\sqrt{s}/kW\sqrt{mm}$
Critical Ignition Flux ($\dot{q}''_{o,ig}$)	22.4 kW/m^2
Minimum Flux for Spread ($\dot{q}''_{o,s}$)	12.37 kW/m^2
Minimum Temperature for Spread ($T_{s,min}$)	307°C
Flame Heating Parameter (Φ)	32.88 $(kW/m)^2/m$

IMO Flame Spread Test Results – Three of the IMO tests conducted produced flame spread data which were reportable. These data were analyzed in accordance with the procedures in ASTM E 1321 yielding the following results (summarized in Table 7.15 below).

Table 7.15- Flame Spread Properties of Material 9, Based on IMO Flame Spread Tests

Flame Spread Parameter (C)	0.26 $m^2\sqrt{s}/kW\sqrt{mm}$
Critical Ignition Flux ($\dot{q}''_{o,ig}$)	17.4 kW/m^2
Minimum Flux for Spread ($\dot{q}''_{o,s}$)	11.39 kW/m^2
Minimum Temperature for Spread ($T_{s,min}$)	284°C
Flame Heating Parameter (Φ)	13.56 $(kW/m)^2/m$

7.5 Lateral Ignition and Flame Spread Testing Conclusions

Since there are no established pass/fail criteria for the ignition and flame spread test results generated from ASTM E 1321 test protocol, the results can merely be presented for review.

7.5.1 Ignition Testing Conclusions

Of the nine materials tested, four materials did not ignite with consistency. Of the materials that did exhibit reportable ignition results, the following summary table was developed (see Table 7.16).

Table 7.16 – Summary of Ignition Test Results

Parameter	Material				
	3	**4**	**5**	**8**	**9**
Ignition Flux ($\dot{q}''_{o,ig}$) [kW/m²]	14.9	14.5	17.2	12.2	15.7
Ignition Temperature (T_{ig}) [°C]	375	370	453	337	385
Slope (b) [1/√s]	0.0369	0.0340	0.0432	0.0505	0.0370
Pre-heat Time (t*) [s]	735	864	536	392	732
kρc [(kW/m²K)² s]	1.65	1.89	1.73	0.74	1.72
Surface Heat Transfer Coef. (h) [W/m²K]	41.99	41.48	50.39	38.48	43.01

7.5.2 ASTM Flame Spread Test Results

The ASTM E 1321 protocol produced reportable results in three of the nine materials tested. Although materials were tested in accordance with the standard, flame spread on the samples was difficult to characterize. One reason for the poor ignition and flame spread characteristics of materials tested under the ATM E1321 protocol may lie in the often lengthy preheat time. As noted for several samples, preheat times were lengthy (on the order of 7-10 minutes) and allowed for the pyrolysis of material in the absence of a pilot. When the pilot is finally added, the surface pyrolysis characteristics of the surface had time to change from the conditions realized during the ignition test. The result is either no ignition or weak ignition of the sample. Furthermore, the changes imposed on the sample surface during the pre-heat led to a different type of burning behavior. This was evidenced by the propensity for oscillating flames rather than sustained flaming, once ignition did occur.

Three materials exhibited reportable flame spread results, which are summarized in Table 7.17.

Table 7.17 – Summary of Flame Spread Characteristics Derived from ASTM E 1321 Testing

Parameter	Material			
	3	**4**	**8**	**9**
Flame Spread Parameter © [$m^2 s^{1/2}$/kW $mm^{1/2}$]	0.22	0.42	0.22	0.17
Ignition Flux ($\dot{q}''_{o,ig}$) [kW/m^2]	19.0	21.7	14.7	22.4
Flux for Spread ($\dot{q}''_{o,s}$) [kW/m^2]	12.83	16.94	8.27	12.37
Temperature Necessary for Spread ($T_{s,min}$) [°C]	325	428	234	307
Flame Heating Parameter (Φ) [$(kW/m)^2/m$]	19.47	6.26	10.47	32.88

7.5.3 Flame Spread Results Based on IMO Flame Spread Tests

Data obtained from four materials tested per the IMO surface flammability standard were analyzed in accordance with the ASTM E 1321 procedure for determining flame spread properties. A summary of the findings is presented in Table 7.18.

Table 7.18 – Summary of Flame Spread Characteristics Derived from IMO Testing

Parameter	Material			
	3	**4**	**8**	**9**
Flame Spread Parameter © [$m^2\sqrt{s}$/kW $\sqrt{mm}$]	0.44	0.24	0.16	0.26
Ignition Flux ($\dot{q}''_{o,ig}$) [kW/m^2]	15.8	16.5	19.1	17.4
Flux for Spread ($\dot{q}''_{o,s}$) [kW/m^2]	16.24	16.55	6.04	11.39
Temperature Necessary for Spread ($T_{s,min}$) [°C]	406	419	177	284
Flame Heating Parameter (Φ) [$(kW/m)^2/m$]	4.79	18.37	18.92	13.56

7.5.4 Conclusions

Poor ignition during the ASTM E 1321 flame spread tests may lie in the often lengthy preheat time. As noted for several samples, preheat times were lengthy (on the order of 7-10 minutes), and allowed for the pyrolysis of material in the absence of a pilot. When the pilot is finally added, the surface pyrolysis characteristics of the surface had time to change from the conditions realized during the ignition test. The result is either no ignition or weak ignition of the sample. Furthermore, the changes imposed on the sample surface during the pre-heat lead to a different type of burning behavior. This was evidenced by the propensity for oscillating flames rather than sustained flaming, once ignition did occur.

The flame-spread values obtained for a material are strongly dependent on the consistency of the material to propagate a flame. Several materials tested did not propagate flame well; the results were sets of data in which flame spread was uncertain due to oscillating flame fronts and/or inconsistent surface burning. Materials exhibiting good flame front propagation were relatively easy to characterize and produced repeatable results.

8.0 DATA ANALYSIS

8.1 Introduction

The main objective of this program is to develop recommendations for ISO 5660 acceptance criteria for fire restricting materials. Extensive small-scale ignition, flame spread, heat release rate, and smoke production rate data were obtained for the nine lining materials in the Cone calorimeter (see Section 5) and the Lateral Ignition and Flame Spread Test (see Section 7). Thus, it would be possible to obtain material properties in various ways, and to predict room/corner test performance using one of the many computer models that are available. A model that produces predictions which are in reasonable agreement with the room/corner test results obtained in this program, could subsequently be used in a sensitivity study to establish a set of response curves that show how room/corner test performance is affected by variations in the input data. Finally, the curves could then be used to establish conservative ISO 5660 acceptance criteria for fire restricting materials.

A search was made of the fire databases at the National Institute of Standards and Technology (NIST) and Worcester Polytechnic Institute (WPI) to find publications on the subject of predicting room/corner test performance on the basis of material data from the Cone calorimeter and other small-scale test methods. As a result of the search, 11 methods were identified. A distinction can be made between two types of methods: simulation models and statistical correlations. The models predict how the room environment varies as a function of time, and how flames spread over the walls and ceiling of the compartment. There is a strong interaction between the two because the conditions in the room determine the heat that is transferred back to the wall and ceiling surfaces, which affects the flame spread and the heat release and smoke production rate of burning sections. The model developed by Quintiere[2], and subsequently

[2] Quintiere, J.G. 1993. "A Simulation Model for Fire Growth on Materials Subject to a Room-Corner Test," *Fire Safety Journal*, 20:313-339.

modified by Janssens et al.[3] and Wade[4], was identified as the best candidate for our purpose.

However, before embarking on a rather tedious modeling exercise, it was decided to first explore some of the less complex prediction methods. Correlations are useful to obtain a better understanding of the relationships between full-scale and small-scale test performance, and to identify possible outliers with a behavior that is inconsistent with the general trends. Correlations for fire growth in the room corner test are typically concerned with predictions of the time to flashover. The acceptance criteria for fire restricting materials are more stringent than flashover criteria, because the limits for heat release rate are below those that are typically associated with flashover conditions in the ISO 9705 room (approximately 1000 kW of total heat release rate). However, all lining materials that exceeded the heat release limits for fire-restricting materials in the room/corner tests resulted in flashover. Therefore, flashover correlations should be quite useful to predict whether a material will meet the heat release criteria for fire restricting materials.

8.2 Quintiere's Propagation Parameter

Quintiere[5] developed a simple method to estimate whether a lining material will go to flashover in the ISO 9705 room/corner test. The assessment is based on the value of a propagation parameter, b, which is defined as follows:

$$b \equiv 0.01\ \dot{q}_{avg}'' - 1 - t_{ig}/\ t_b$$

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[3] Janssens, M.L., M.A. Dietenberger, O. Grexa. and R.H. White. 1995. "Predictions of ISO 9705 Room/Corner Test Using a Simple Model," in *Proceedings of the 4th Fire and Materials Conference*, Interscience Communications, London, UK, 73-83.

[4] Wade, C. 1996. "A Room Fire Model Incorporating Fire Growth on Combustible Lining Materials," M.S. Thesis, Worcester Polytechnic Institute, Worcester, MA.

[5] Quintiere, J.G., and C.H. Lee, 1998. "Ignitor and Thickness Effects on Upward Flame Spread," *Fire Technology*, 34:18-38.

where b = propagation parameter (no units)

$\dot{q}_{avg}$" = test-average heat release rate measured in the Cone calorimeter (kW/m^2)

t_{ig} = ignition time measured in the Cone calorimeter (s)

t_b = duration of flaming in the Cone calorimeter (s)

Quintiere et al. suggest that $\dot{q}_{avg}$" and t_b be obtained at a heat flux level of 30 kW/m^2 (represents the heat flux from the material's own flame), and that t_{ig} be measured at 60 kW/m^2 (represents the heat flux from the burner flame). A graph of time to flashover as a function of b, obtained as outlined above, shows a sharp transition around b = -1, which is the critical value proposed by Quintiere.

Cone calorimeter data were not obtained at the heat flux levels suggested by Quintiere. Therefore, the propagation parameter, b, was calculated on the basis of Cone calorimeter data obtained at 50 and 75 kW/m^2. Time to flashover is plotted as a function of the first set of propagation parameter values in Figures 8.1 and 8.2. Based on a critical value of –1, this graph indicates that Material No.7 would be mistakenly rejected as a fire restricting material, while Material No. 5 would be mistakenly accepted. Material No. 7 did melt and shrink away from the burner flame in the ISO 9705 room test (see Section 3.4). A material that melts and shrinks when heated continues being exposed to the heat flux from the radiant heater. This explains why Material No. 7 is expected to fail in the room test on the basis of the Cone calorimeter data. The results for Cone calorimeter data at 75 kW/m^2 clearly show that a cut-off value of b = -1 is overly conservative. If b = -0.5 is used, Material No. 7 would still be mistakenly rejected as a fire restricting material, while Material Nos. 5 and 9 would be mistakenly accepted. Since the propagation parameter method would lead to acceptance of some materials that do not meet the requirements for fire restricting materials, it is not conservative. Perhaps a different choice of the heat flux levels at which the Cone calorimeter data have to be obtained could improve the predictive capability of the method.

Figure 8.1 – ISO 9705 Flashover Time as a Function of the 50 kW/m^2 Propagation Parameter

Figure 8.2 –ISO 9705 Flashover Time as a Function of the 75 kW/m^2 Propagation Parameter

8.3 Östman's Smoke Correlations

Östman et al.[6] showed that there is a reasonably linear correlation between the maximum or average smoke production rates obtained in the room/corner test and in the Cone calorimeter. Figures 8.3 and 8.4 compare the test-average and maximum 60-second sliding average smoke production rates, respectively. The Cone calorimeter data are those obtained at 50 kW/m^2.

Figure 8.3 – Correlation of Test-Average Smoke Production Rates

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6 Östman, B.A.-L., and L. D. Tsantaridis. 1991. "Smoke Production in the Cone Calorimeter and the Room Fire Test," *Fire Safety Journal*, 17:27-43

Figure 8.4 – Correlation of Maximum 60-Second Sliding Average Smoke Production Rates

In Figure 8.3 there are five materials that form a cluster close to the origin. Material No. 9 is a low-smoke modified acrylic composite. The room/corner test on this material flashed over, therefore, this material did not meet the heat release rate criteria for fire restricting materials. Consequently, this material does not need to be considered in the establishment of ISO 5660 acceptance criteria for smoke. The horizontal dashed line in the graph delineates the boundary between pass and fail in the room tests. Two of the materials in this region met the smoke criteria for fire restricting materials in the room/corner test. The remaining two materials marginally failed. The most recent proposed cut-off by Finland (test-average smoke production rate in the Cone calorimeter at 50 kW/m^2 of 0.005 m^2/s) is shown as a vertical dashed line on the graph. It appears to be successful in isolating the four materials that performed well in the room/corner test. However, a test-average smoke production rate in the Cone calorimeter at 50 kW/m^2 of 0.005 m^2/s or less does not guarantee that the test-average smoke production rate in the room test will not exceed the limit of 1.4 m^2/s. The average smoke production rate in the room test that corresponds to SPR_{avg} = 0.005 m^2/s is approximately 2.5 m^2/s.

The data points for the same five materials are clustered around zero in Figure 8.4. A Cone calorimeter limit of 0.01 m^2/s would eliminate all materials, except Nos. 1, 2, 6, and 7 (see vertical dashed line in Figure 8.4). Materials with an $SPR_{60, max}$ = 0.01 m^2/s in the Cone calorimeter, might have an $SPR_{30, max}$ in the room that slightly exceeds the limit for fire restricting materials of 8.4 m^2/s, but would be less than 10 m^2/s.

8.4 Data Analysis Conclusions

The test data presented in earlier sections and the previous discussions are consistent with the proposal by Finland regarding the ISO 5660 acceptance criteria for fire restricting materials, with the following exceptions.

The ignition time criterion should be lowered from 30 to 20 seconds to avoid Material No. 7 being eliminated on this basis. All nine materials tested in this study meet the 20-second ignition criterion. However, an ignition time criterion is probably needed to catch materials that ignite very quickly, but produce little heat and smoke. A typical example of such a material is a mineral insulation with paper facing. Flames could spread very quickly over the surface of this material in the room/corner test, with little heat release and smoke production due to the limited amount of fuel present.

Based on the data presented in Section 5.4 and Appendix C.1, there is no clear reason to change the heat release limits proposed by Finland. The smoke limits are changed on the basis of the discussion in the previous section. A restriction of $SPR_{60, max}$ might not be necessary.

In summary, the following set of ISO 5660 acceptance criteria is consistent with this study:

- Time to ignition (t_{ig}) greater than 20 seconds.
- Maximum 60-second sliding average heat release rate ($HRR_{60,max}$) less than 60 kW/m^2.
- Total heat release (THR) less than 12 MJ/m^2.
- Maximum 60-second sliding average smoke production rate ($SPR_{60, max}$) less than 0.01 m^2/s.
- Average smoke production rate (SPR_{avg}) below 0.005 m^2/s.

Due to time constraints, the use of computer models to further refine the acceptance criteria could not be explored. Since the necessary full-scale and small-scale data are available, it is recommended that this be pursued at a later date.

9.0 CONCLUSIONS AND RECOMMENDATIONS

The following recommendation can be made on the basis of the results obtained in this program:

- The room tests on contents confirmed that materials, which meet the requirements for fire restricting linings, could safely be used as framing materials and components of furniture and contents. The requirements could perhaps be relaxed, but a hazard or risk assessment is needed to develop revised acceptance criteria that do not compromise safety.

- The IMO surface flammability test criteria for finish materials appear to be correlative to those for fire restricting lining materials. Four materials that met the heat release criteria for fire restricting materials also met the IMO surface flammability requirements for bulkhead and ceiling linings. Four materials failed both sets of criteria. Only material No. 5 met the IMO surface flammabilty criteria, but failed in the room/corner test. However, the time to flashover was the longest for this material, so there seems to be some consistency between the two tests.

- It is recommended that the preheat be eliminated from the ASTM E 1321 flame spread test protocol, because it creates major problems for fire retardant treated composite materials. It is suggested to run the flame spread tests as specified in the IMO surface flammability test protocol. The procedures for flame spread data analysis described in ASTM E 1321 worked quite well for the IMO flame spread data, which were obtained at a higher heat flux level without preheating of the specimen.

- The following set of ISO 5660 acceptance criteria for fire restricting materials is consistent with the results obtained in this study:

- Time to ignition (t_{ig}) greater than 20 seconds.
- Maximum 60-second sliding average heat release rate ($HRR_{60,max}$) less than 60 kW/m^2.
- Total heat release (THR) less than 12 MJ/m^2.
- Maximum 60-second smoke production rate ($SPR_{60, max}$) less than 0.01 m^2/s.
- Average smoke production rate (SPR_{avg}) below 0.005 m^2/s.

♦ Based on the analysis of the data obtained in this program, the room/corner test smoke limits that correspond to the cone calorimeter criteria are 10 m^2/s for the maximum 60-second sliding average and 2.5 m^2/s for the test average.

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